

Using Multispacecraft Observations, Modeling, and Numerical Simulations to Tell the Story of the Coronal Origins of the 2007 May 19–23 ICMEs

B. J. Lynch¹

A. A. Reinard², T. Mulligan³, Y. Li¹, J. G. Luhmann¹, G. H. Fisher¹,
J. K. Edmondson⁴, J. C. Allred⁵, P. J. MacNeice⁵, C. R. DeVore⁵,
S. K. Antiochos⁵, K. K. Reeves⁶, C. E. Rakowski⁷, J. M. Laming⁷, J. A. Linker⁸

[1] SSL/Univ. of California Berkeley

[2] CIRES/Univ. of Colorado & SWPC/NOAA

[3] SSD/The Aerospace Corporation

[4] AOSS/Univ. of Michigan

[5] NASA Goddard Space Flight Center

[6] CFA/Harvard Smithsonian Observatory

[7] SSD/Naval Research Laboratory

[8] Predictive Science, Inc.

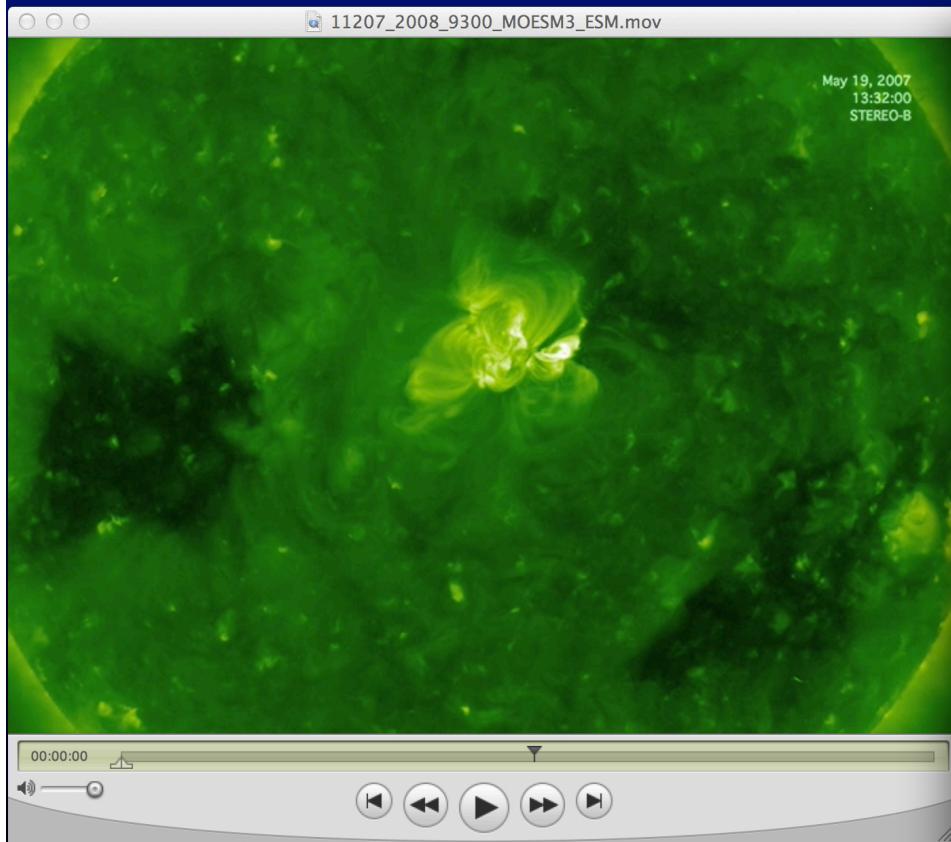
Work supported by

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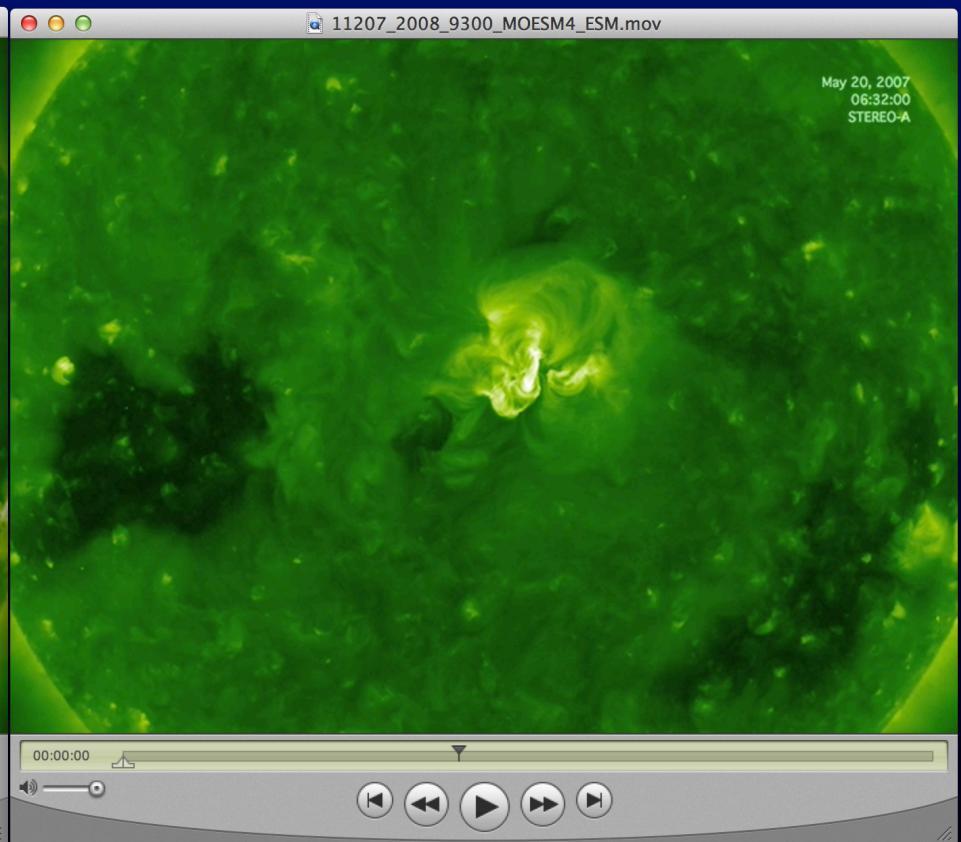
1. Overview of the Consecutive Eruptions of 19—20 May 2007
 - Magnetic Field Structure, Remote and Multispacecraft In-Situ Observations
 - 21—23 May 2007 ICME Flux Rope Structure and Orientation
2. New Technique for Spatial Mapping/Interpolation of Multispacecraft Data
 - Demonstration & Solar Wind Test Period
 - 21—23 May 2007 Flux Rope ICMEs and Their Surroundings
3. Comparison of Multispacecraft Ionic Composition Data with Recent Modeling of Charge States Derived from MHD Simulations of CME Initiation
4. What Can We Learn from an Integrated Data Analysis/Modeling/Simulation Approach?
 - “Telling the Story” of the 19—20 May 2007 CME Eruption Scenario

19–20 May 2007 CMEs from AR 10956: Well-Studied Event(s) w/ Excellent STEREO Coverage

STEREO A EUVI 195
2007 MAY 19 – 12:52UT – CME #1

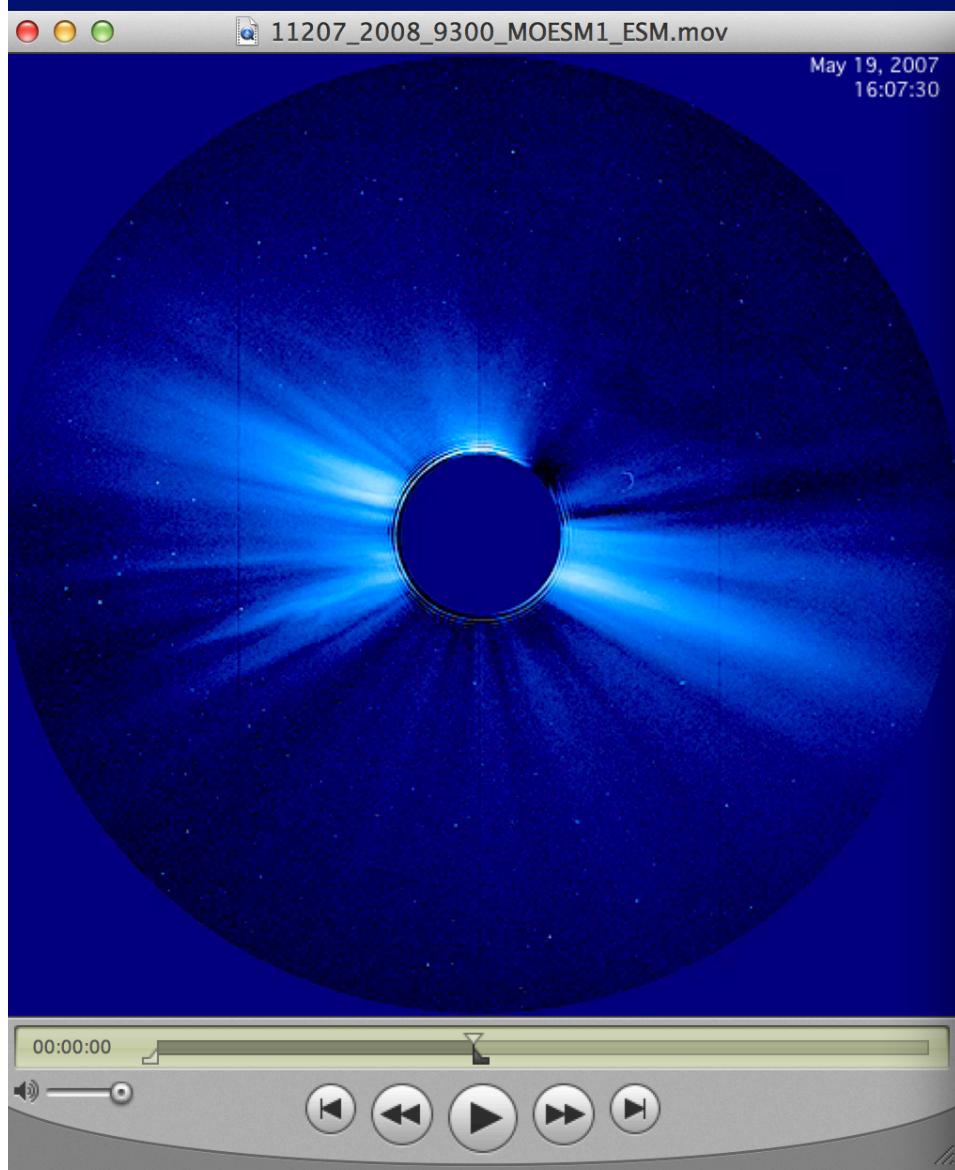


STEREO A EUVI 195
2007 MAY 20 – 04:52UT – CME #2

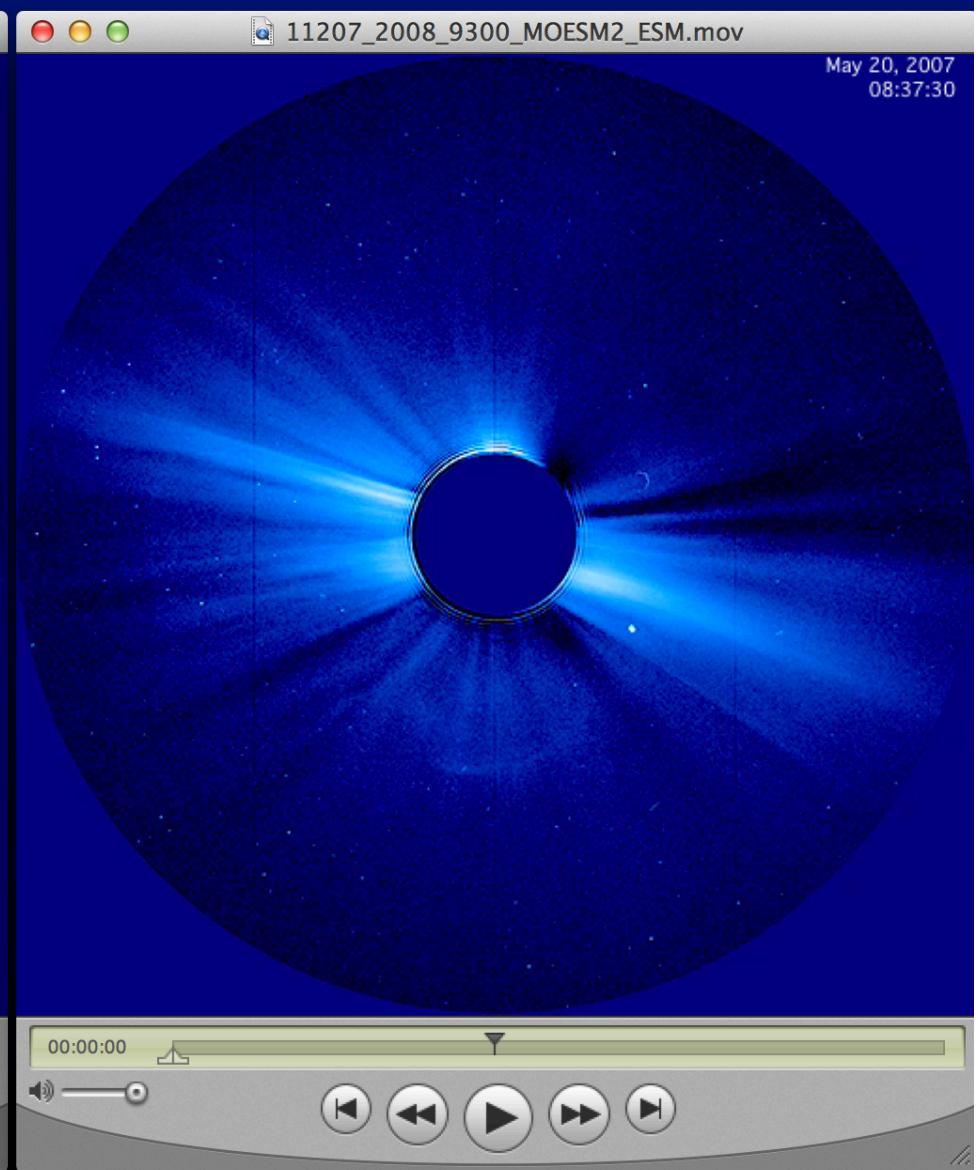


19–20 May 2007 CMEs from AR 10956: Well-Studied Event(s) w/ Excellent STEREO Coverage

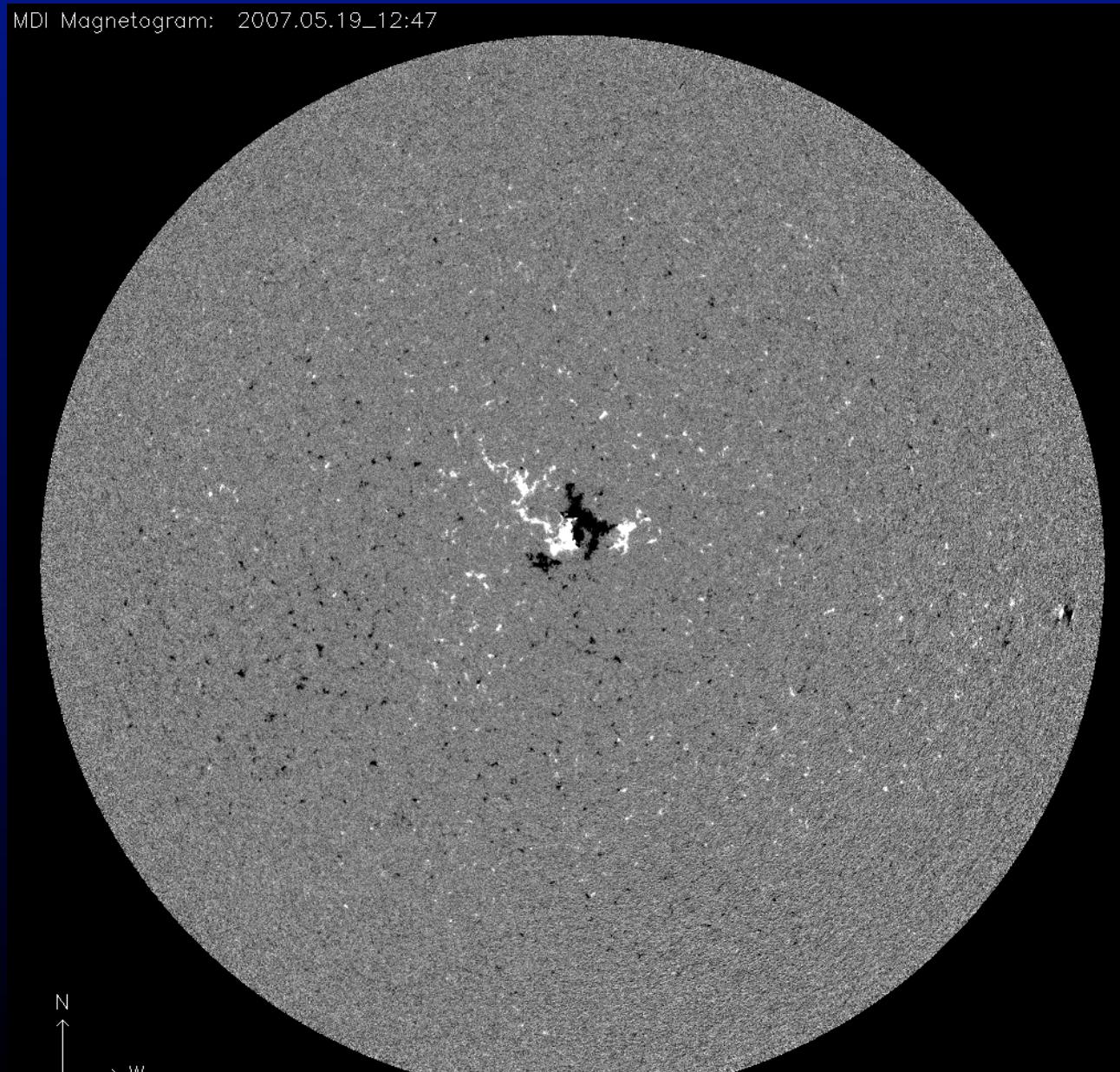
2007 MAY 19



2007 MAY 20



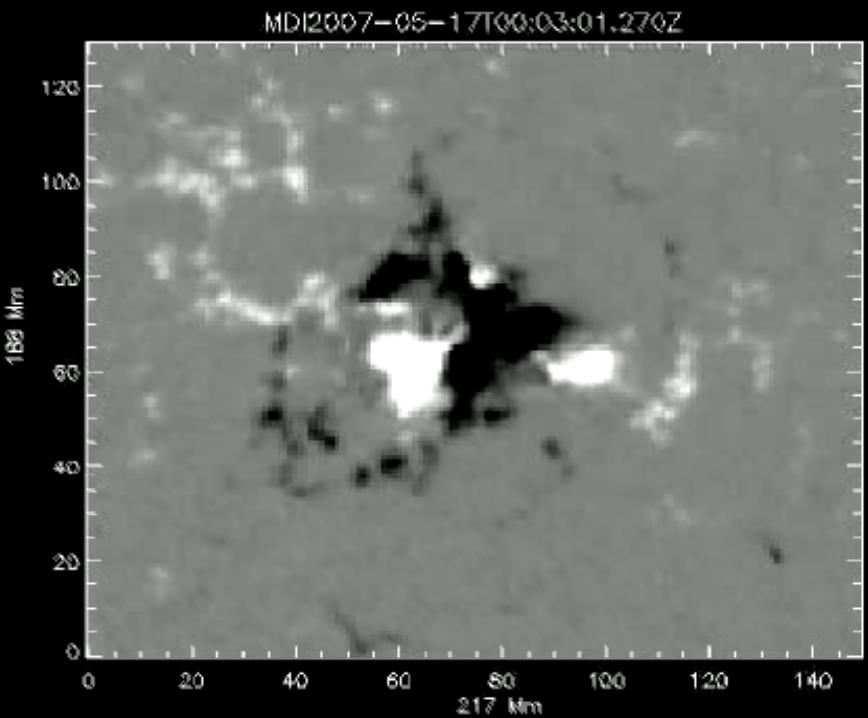
19–20 May 2007 CMEs from AR 10956: Well-Studied Event(s) w/ Excellent STEREO Coverage



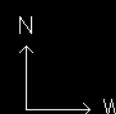
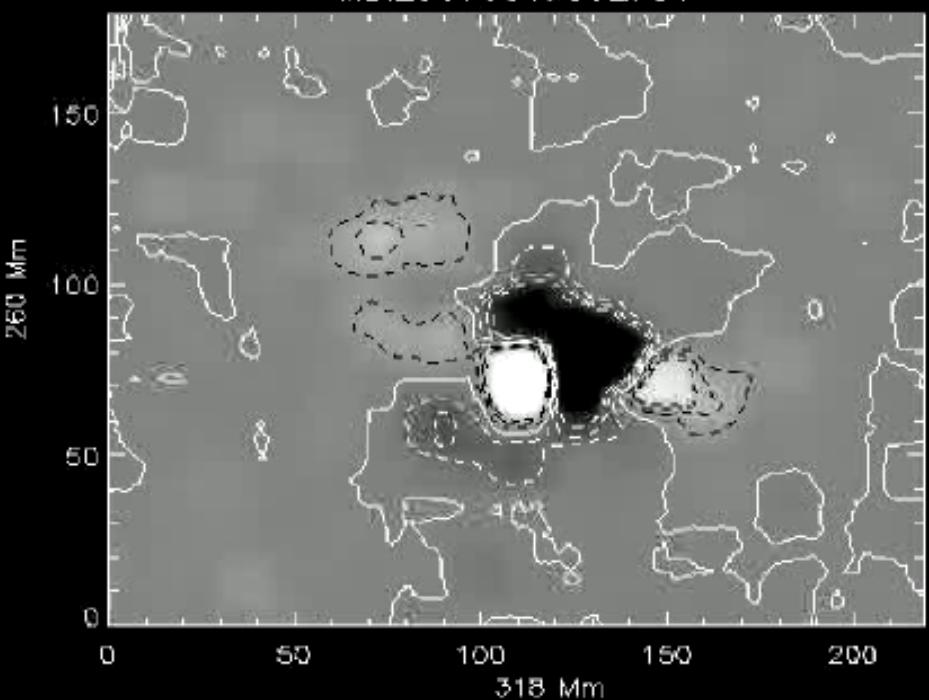
Plot Made 1-Nov-2007

19–20 May 2007 CMEs from AR 10956: Well-Studied Event(s) w/ Excellent STEREO Coverage

MDI Magnetogram: 2007.05.19_12:47

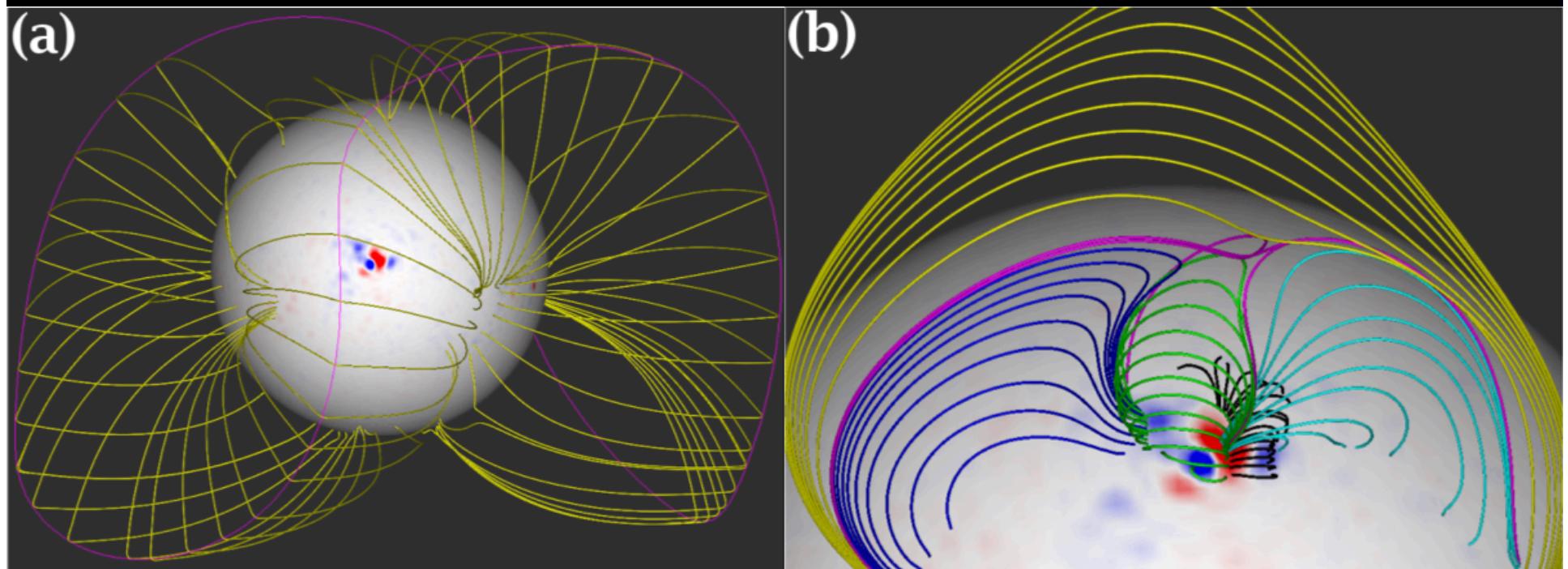


MDI2007-05-17T00:03:01.270Z

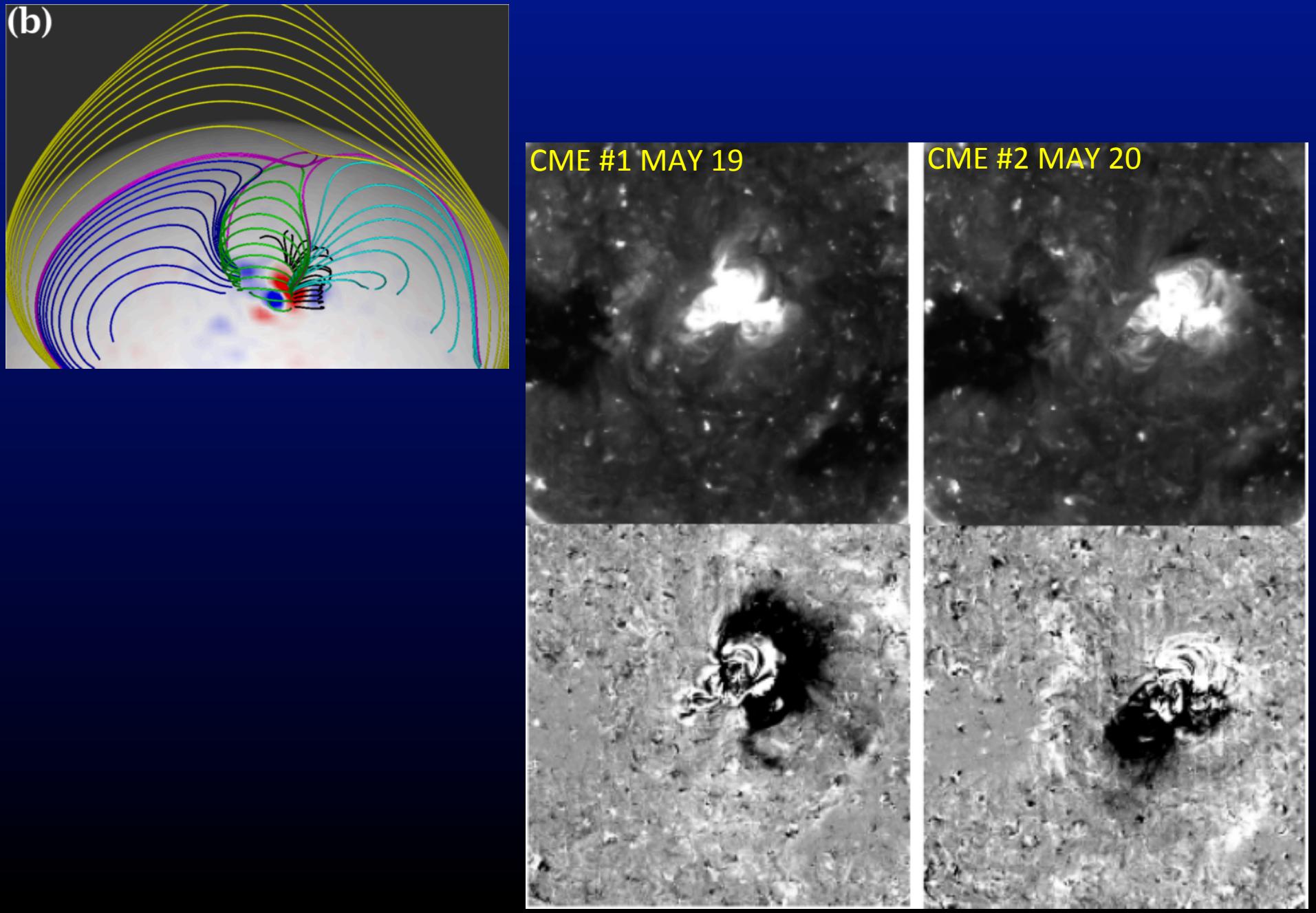


19–20 May 2007 CMEs from AR 10956: Well-Studied Event(s) w/ Excellent STEREO Coverage

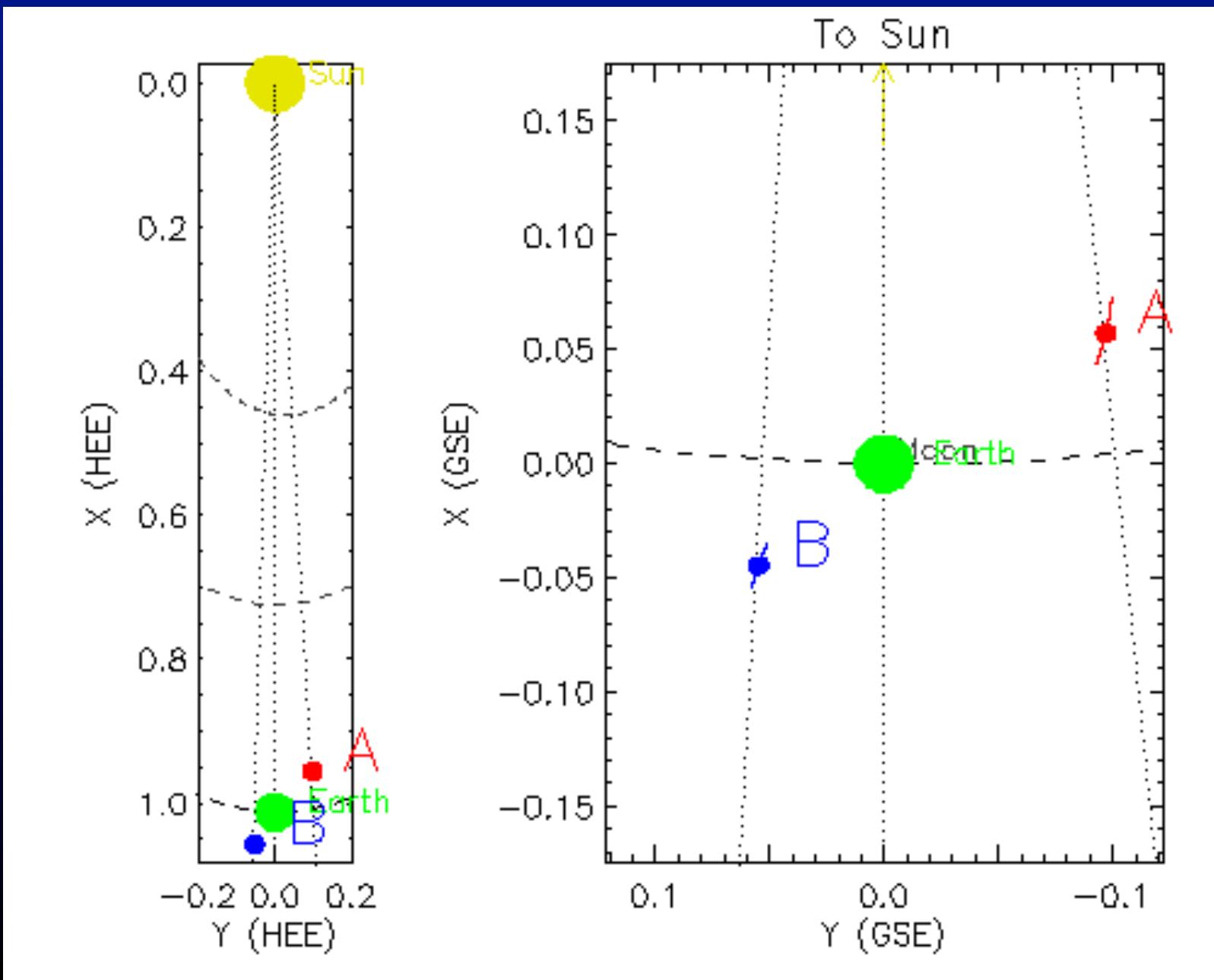
e.g., Li et al. (2008, ApJ, 681, L37), Bone et al. (2009, SoPh, 259, 31), Liewer et al. (2009, SoPh 256, 57), Veronig et al. (2008, ApJ, 681, L113), Gopalswamy et al. (2009, ApJ, 691, L123), Attrill (2010, ApJ, 718, 494), Kerdraon et al. (2010, ApJ, 715, 468), Mierla et al. (2008, SoPh, 252, 385)



19–20 May 2007 CMEs from AR 10956: Well-Studied Event(s) w/ Excellent STEREO Coverage

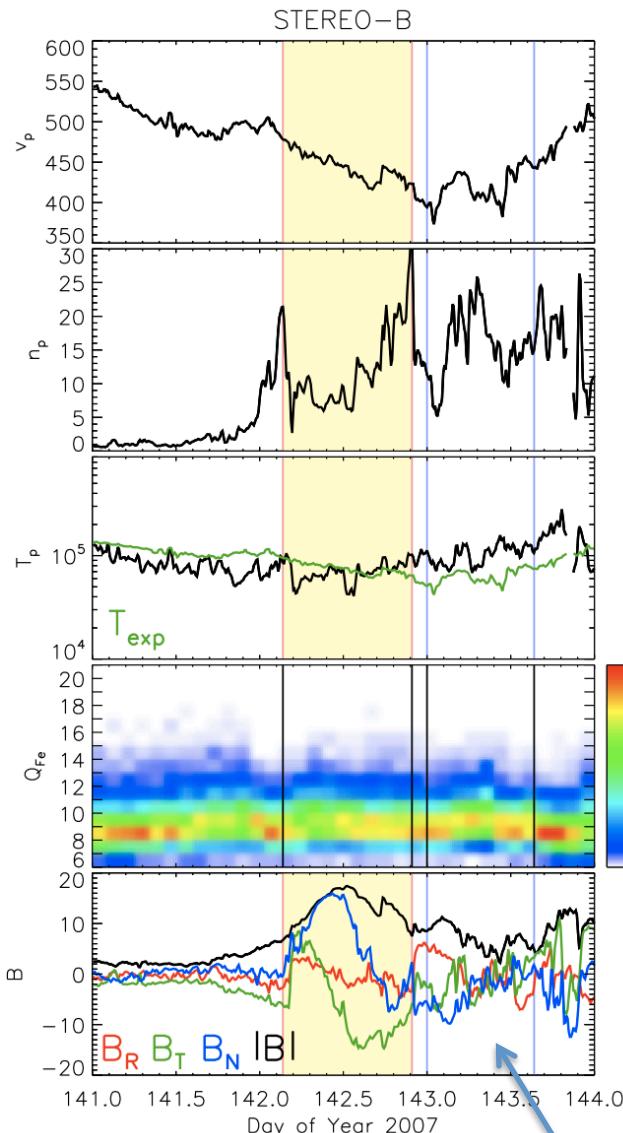


21–23 May 2007 ICMEs Seen In-Situ by STEREO A & B, ACE, and Wind

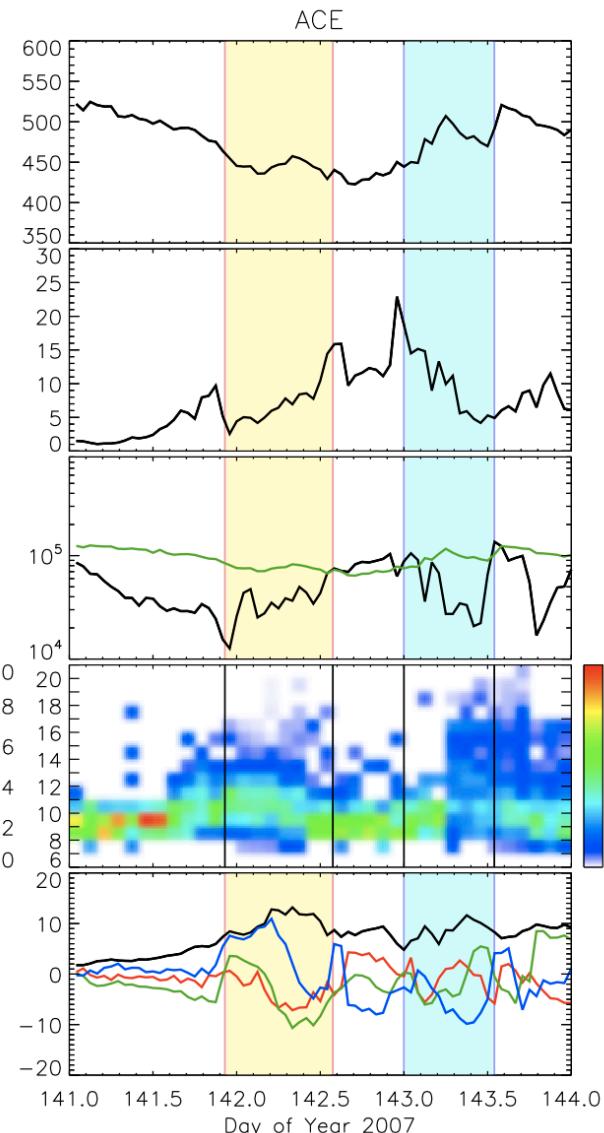


21–23 May 2007 ICMEs Seen In-Situ by STEREO A & B, ACE, and Wind

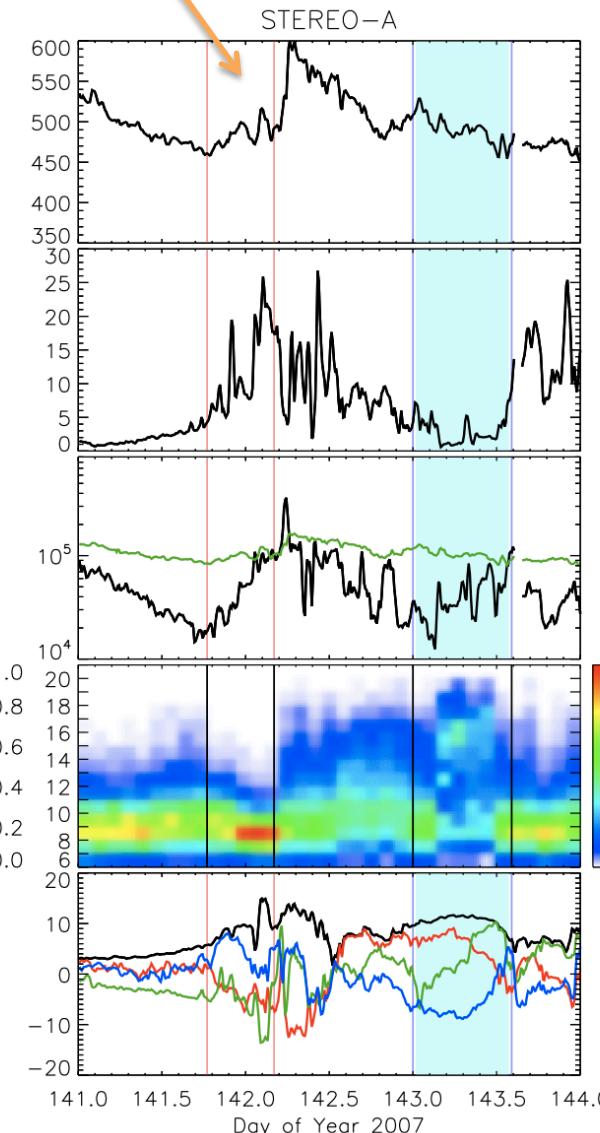
MC1



MC1



MC1 sheath?



MC2 sheath?

MC2

MC2

21–23 May 2007 ICMEs: Also Well-Studied Event(s)

Mulligan & Russell (2001) non-cylindrical flux rope fits. Distorted elliptical cross-sections, highly inclined. Fit multispacecraft magnetic field data along w/ velocity flow deflections.

Other model fits – LFF cylindrical, Grad-Shafranov reconstructions – all show similar orientations, FR sizes, etc.

Up until now, this has been “state-of-the-art” visualization. Doesn’t include non-FR ICME structure (sheath region, background solar wind flow, etc).

See also:

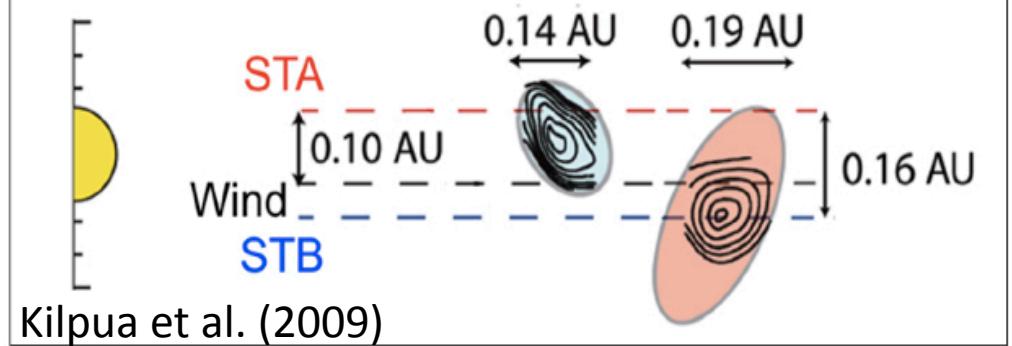
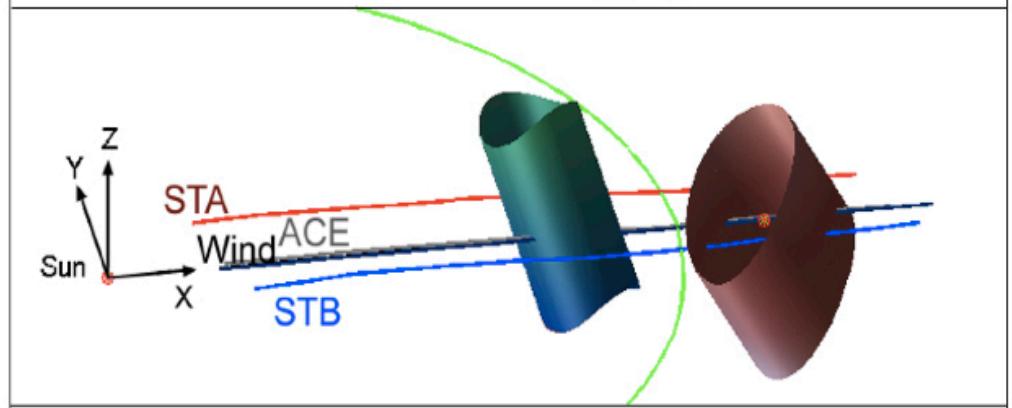
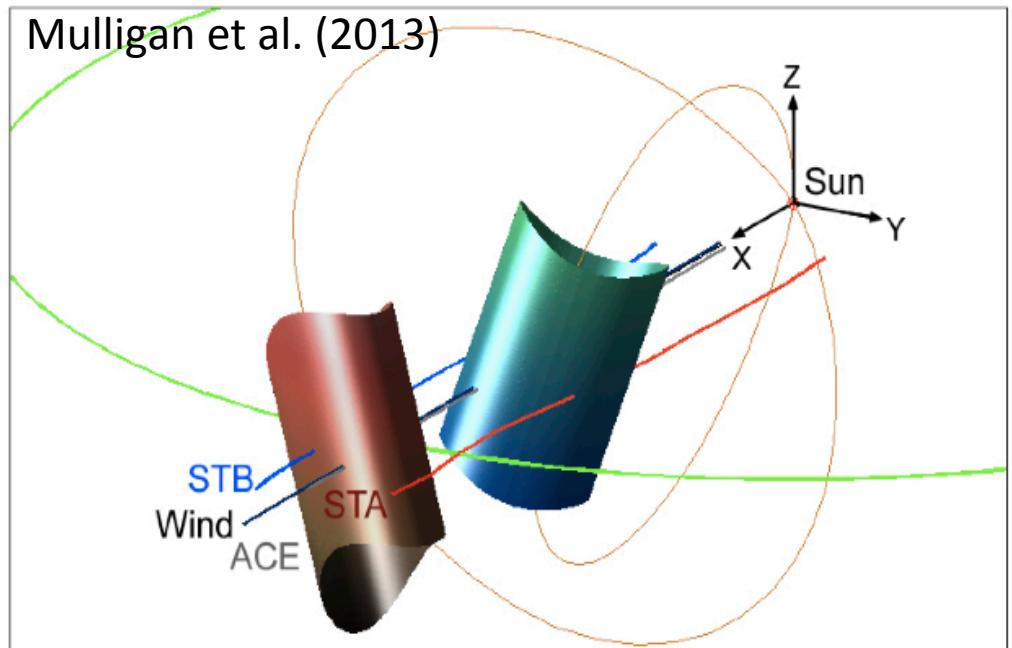
Liu et al. (2008, ApJ, 677, L133)

Kilpua et al. (2009, SoPh, 254, 325)

Möstl et al. (2009, JGR, 114, A08102)

Möstl et al. (2009, SoPh, 256, 427)

Rakowski et al. (2011, ApJ, 730, 30)



Mulligan et al. (2013) Multispacecraft Interpolation: Creating Spatial Maps

Map spacecraft measurements $P(t)$ into spatial function $P(r(t))$ by integrating bulk velocity vector

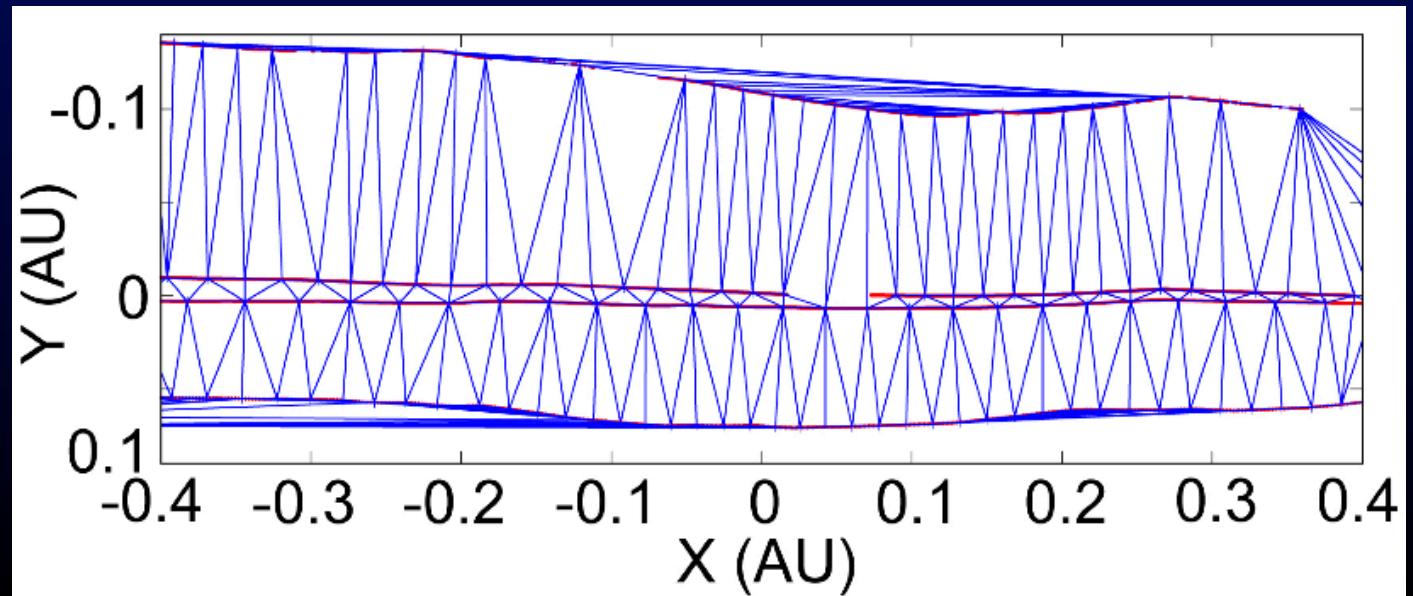
$$\vec{r}_{\pm n} = \vec{r}_0 + \sum_{k=1}^n \pm \vec{v}_k \cdot \Delta t$$

Delaunay Triangulation on set of points P generate set of triangles whose circumcircles contain no points on the interior. Voronoi tessellation forms a cell complex that partitions convex hull – useful in natural neighbor interpolation.

$H(x)$ estimate of function $h_{pi}(x)$ using Interpolating weights λ_{pi} (fraction of area overlap).

$$H(x) = \sum_i^n \lambda_{p_i}(x) h_{p_i}(x), \quad \lambda_{p_i}(x) = \frac{\omega_{p_i}(x)}{\sum_i \omega_{p_i}(x)}$$

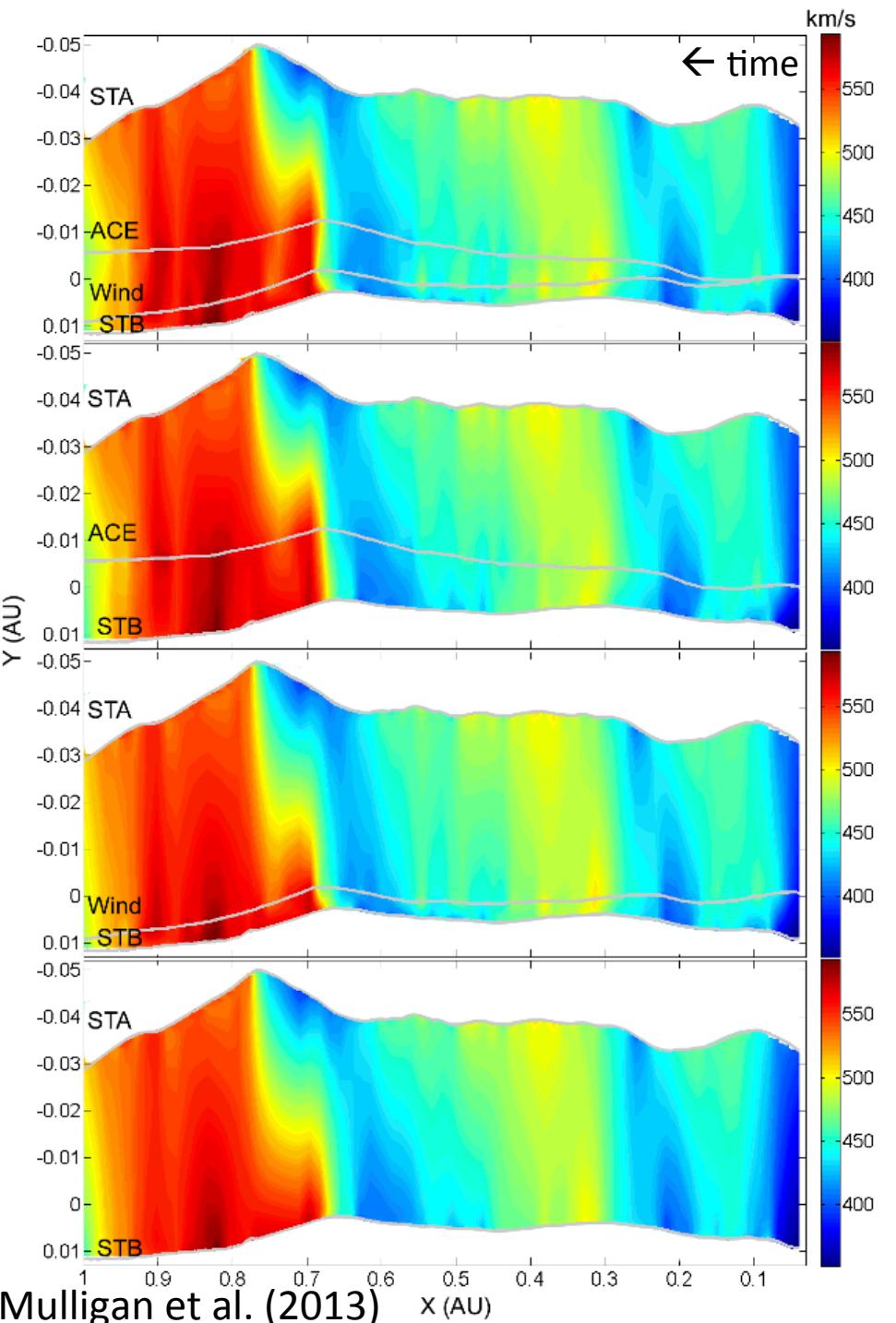
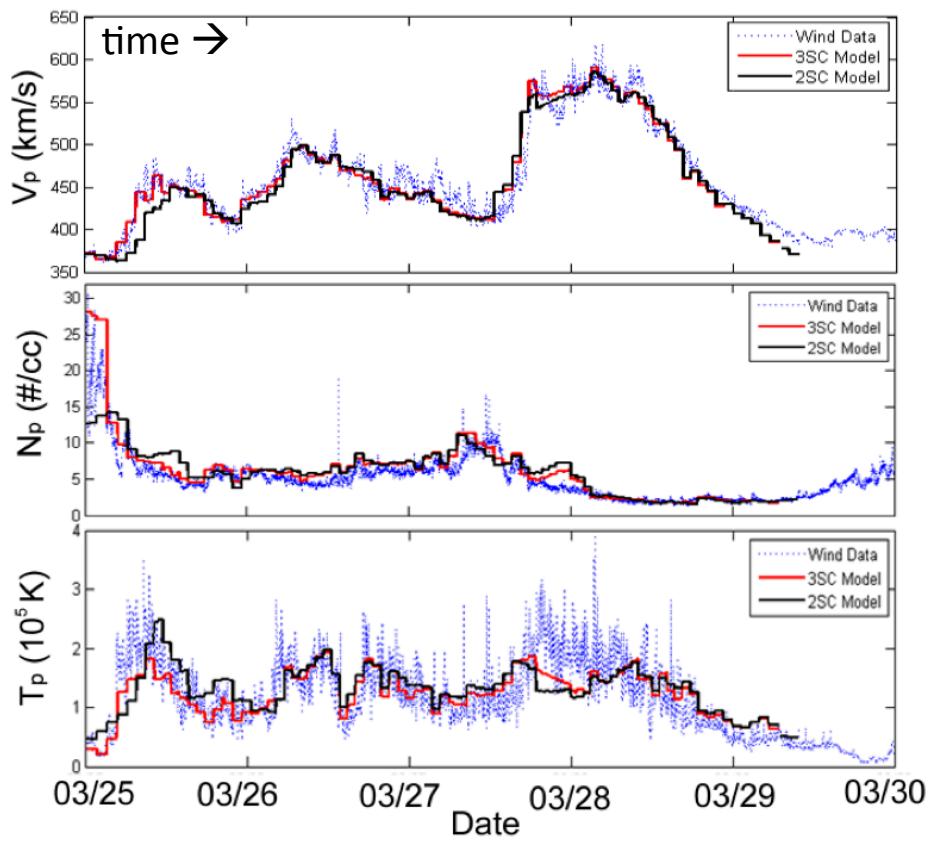
$H(x)$ is a continuous interpolation of underlying function except at original data points.



Test period: 25–30 March 2007

STA, STB separated by $\sim 4^\circ$

2SC: Interpolate between STA, STB data
3SC: Interpolate btwen STA, STB, & ACE
→ compare w/ Wind data



21–23 May 2007 ICMEs: Spatial Maps

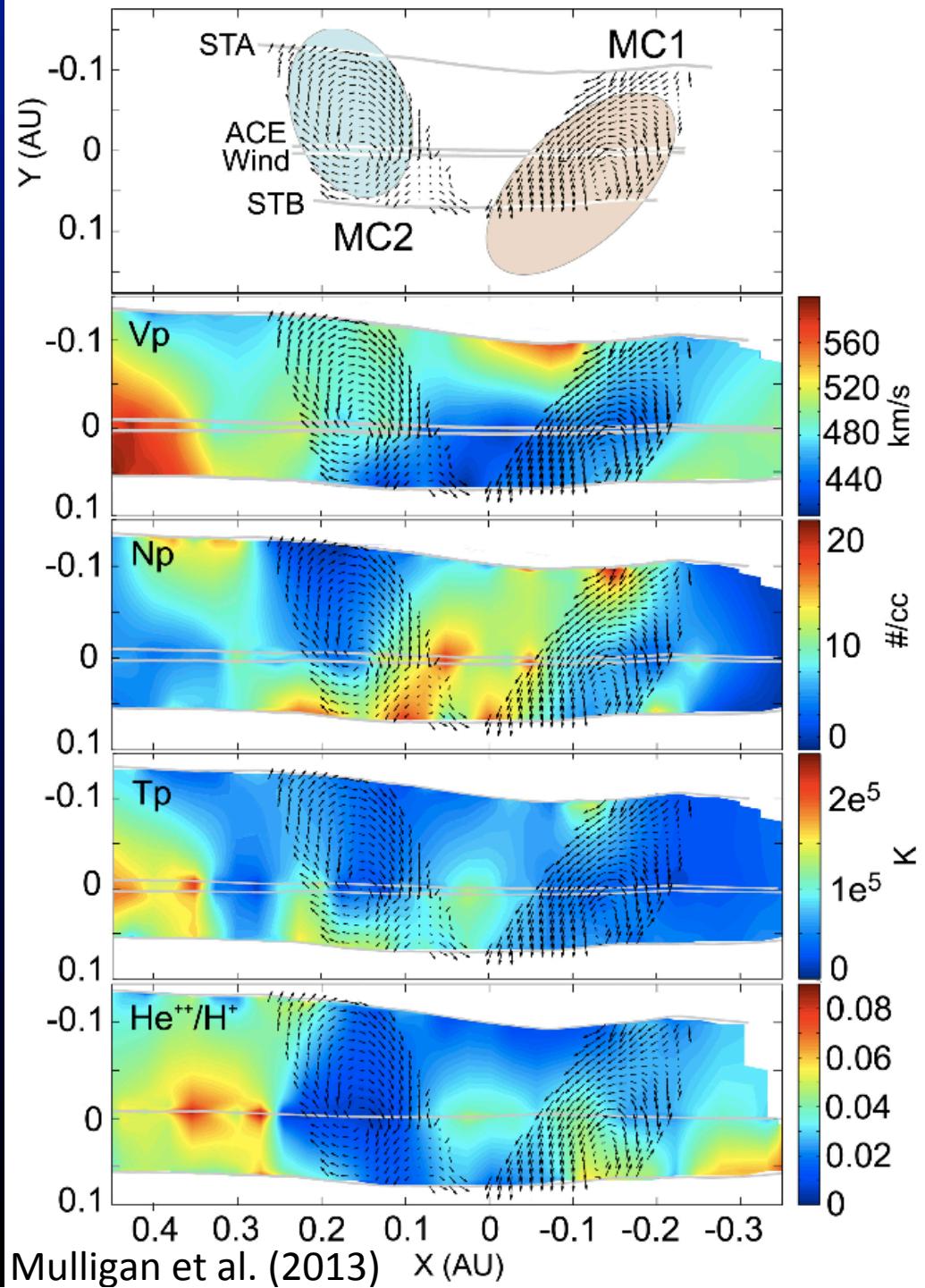
STA, ACE separation $\sim 5.9^\circ$

STB, ACE separation $\sim 3.1^\circ$

STA, STB separation $\sim 9^\circ$

Bulk plasma properties V_p , N_p , T_p , and $\text{He}^{++}/\text{H}^+$ visualized in the context of ICME magnetic flux rope structure (cross-section) and their immediate interplanetary environment.

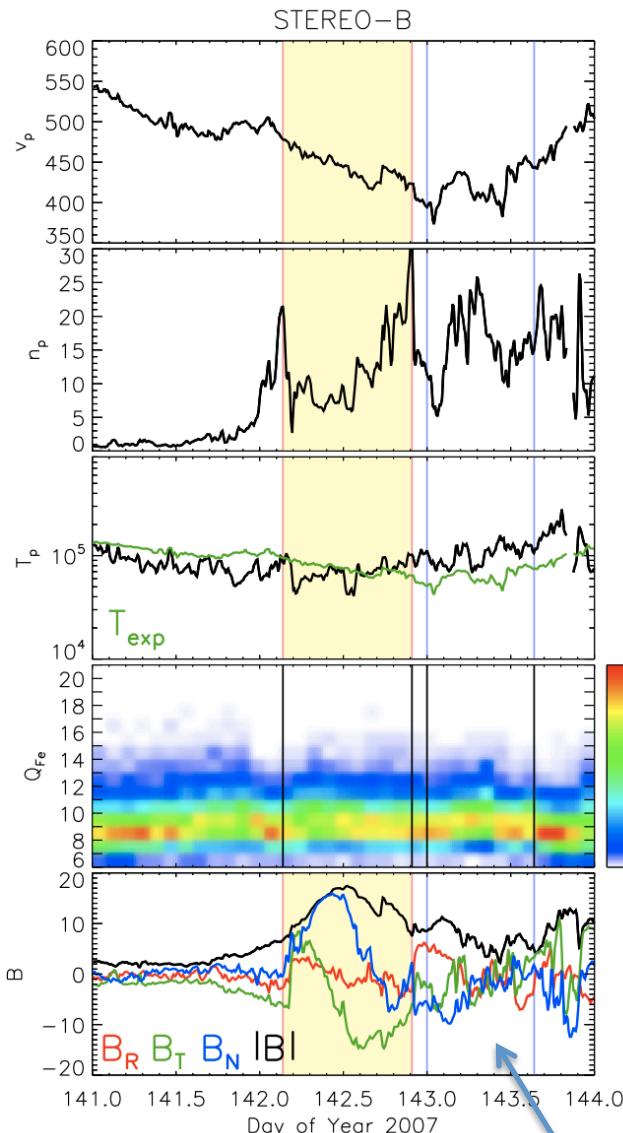
- Flux rope distortion by higher speed regions of solar wind flow.
- Density enhancements/compression structure (pile up) in sheath regions + surrounding flux ropes.
- Significant variation in He^{++} abundance. CME initiation/source region height?



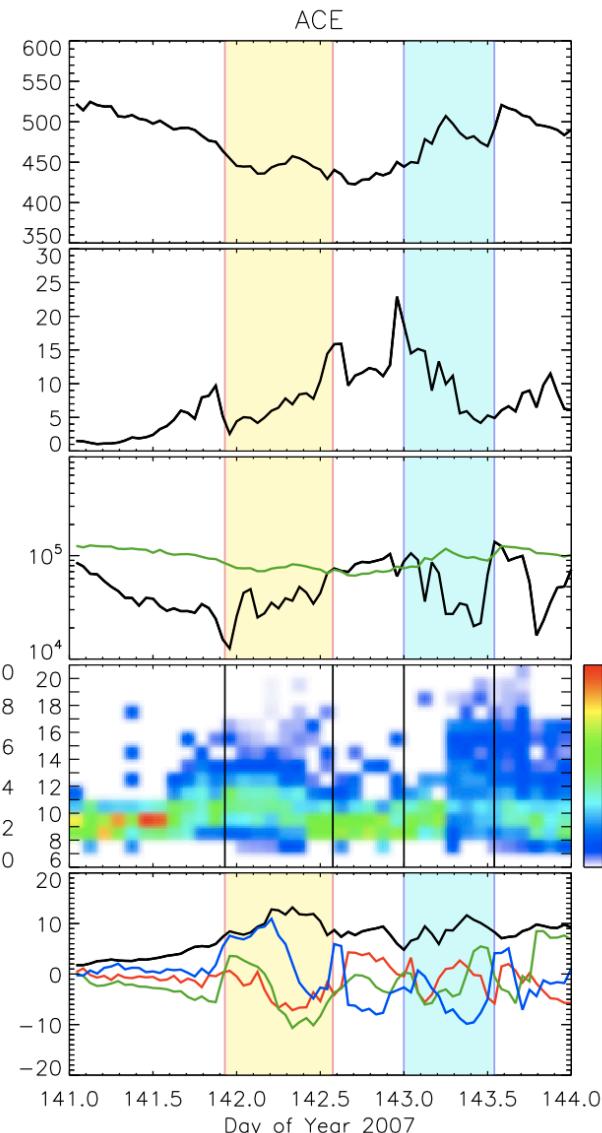
Mulligan et al. (2013)

21–23 May 2007 ICMEs Seen In-Situ by STEREO A & B, ACE, and Wind

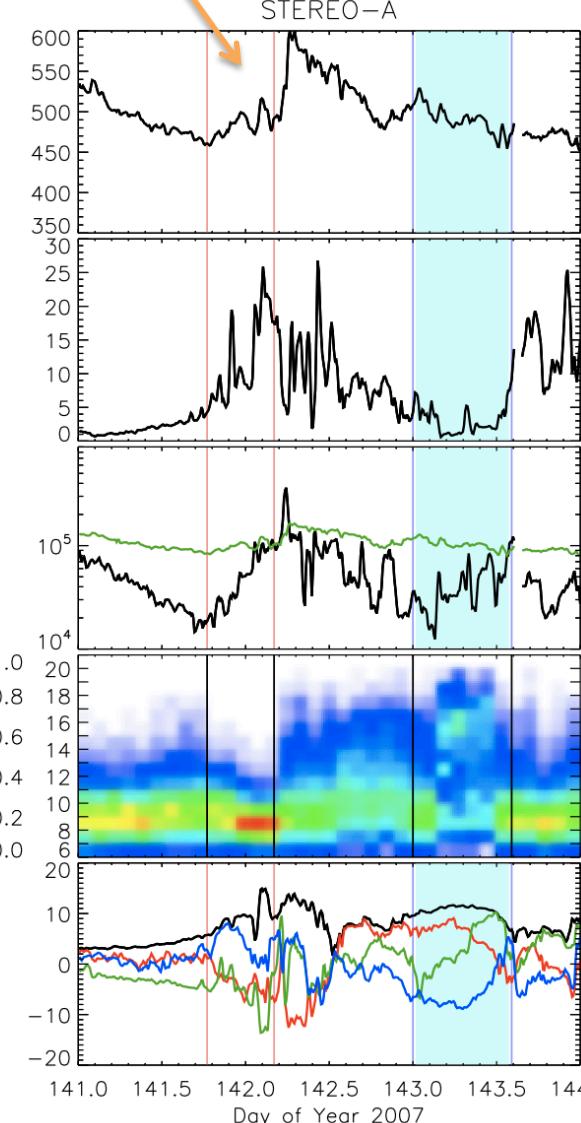
MC1



MC1



MC1 sheath?



MC2 sheath?

MC2

MC2

So what's next? How do we relate the in-situ plasma to the coronal source region? If we have a guess, how do we figure out if it's reasonable?

→ Insights from Modeling

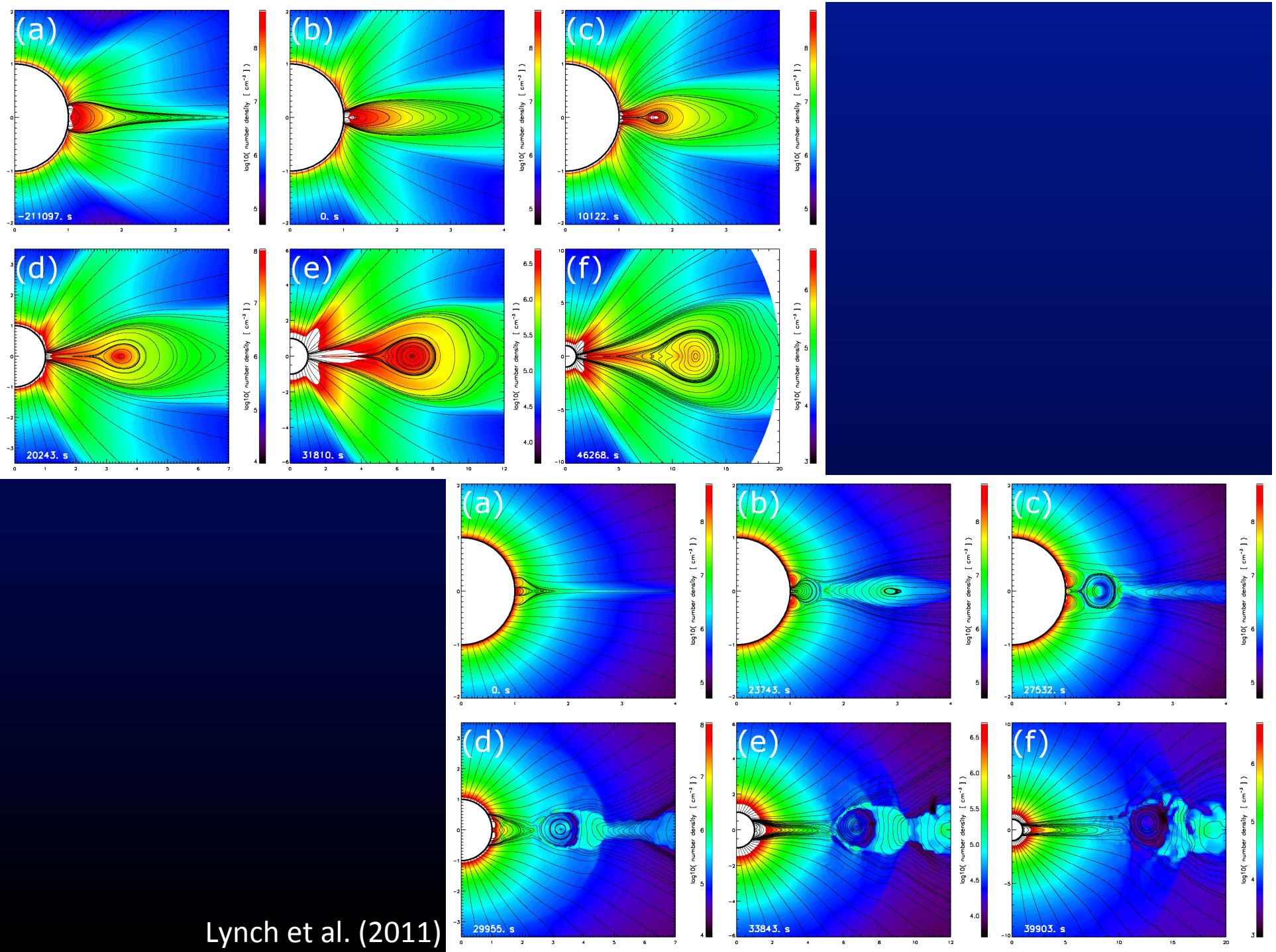
 → Compare In Situ Ionic Composition Data with Modeling of Charge State Evolution

 → Look at Properties of Large-Scale MHD Evolution of CME Initiation and Propagation

→ Combine the two!

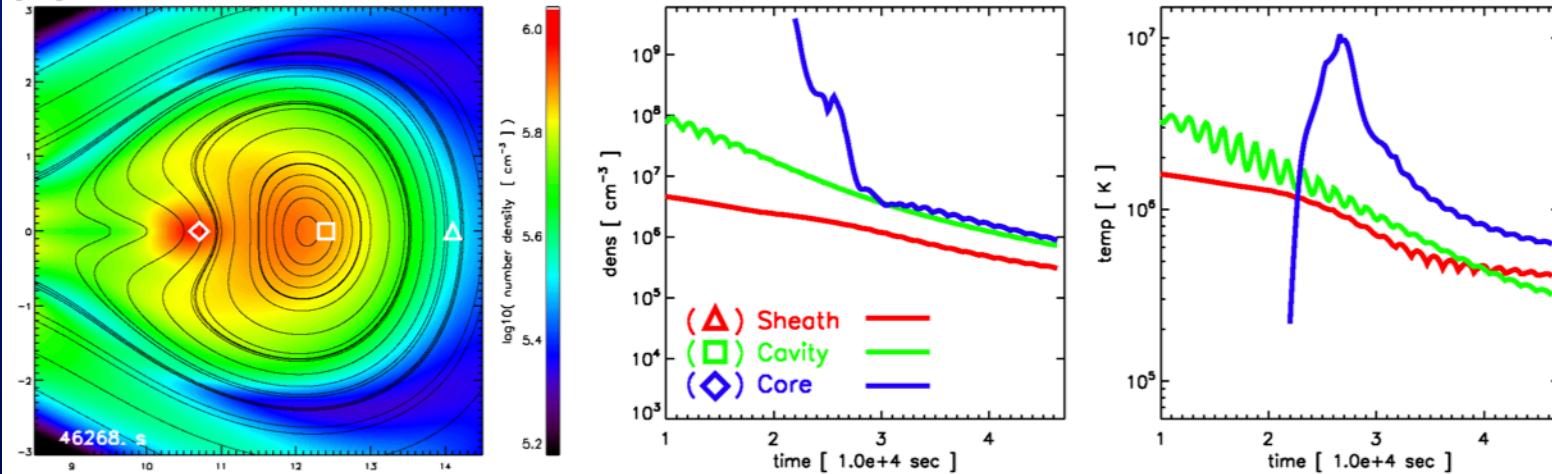
 → Large-Scale MHD Plasma evolution dictates ionic charge evolution

 → Piece everything together into a coherent narrative,
 i.e., "Tell the Story"

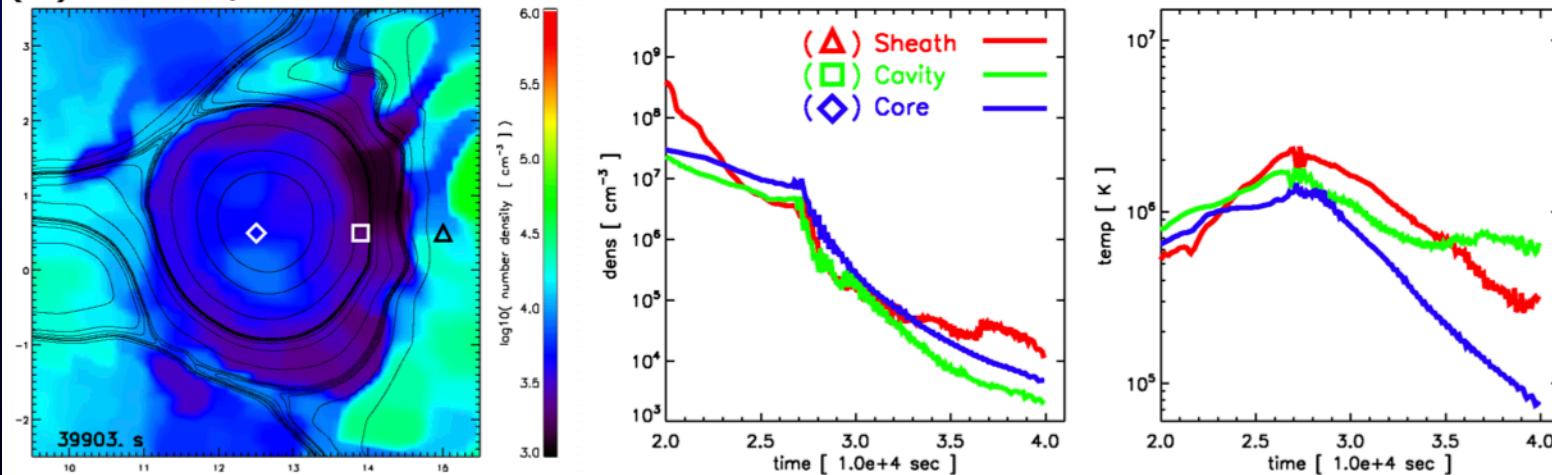


Lynch et al. (2011)

(a) MAS / flux-cancellation



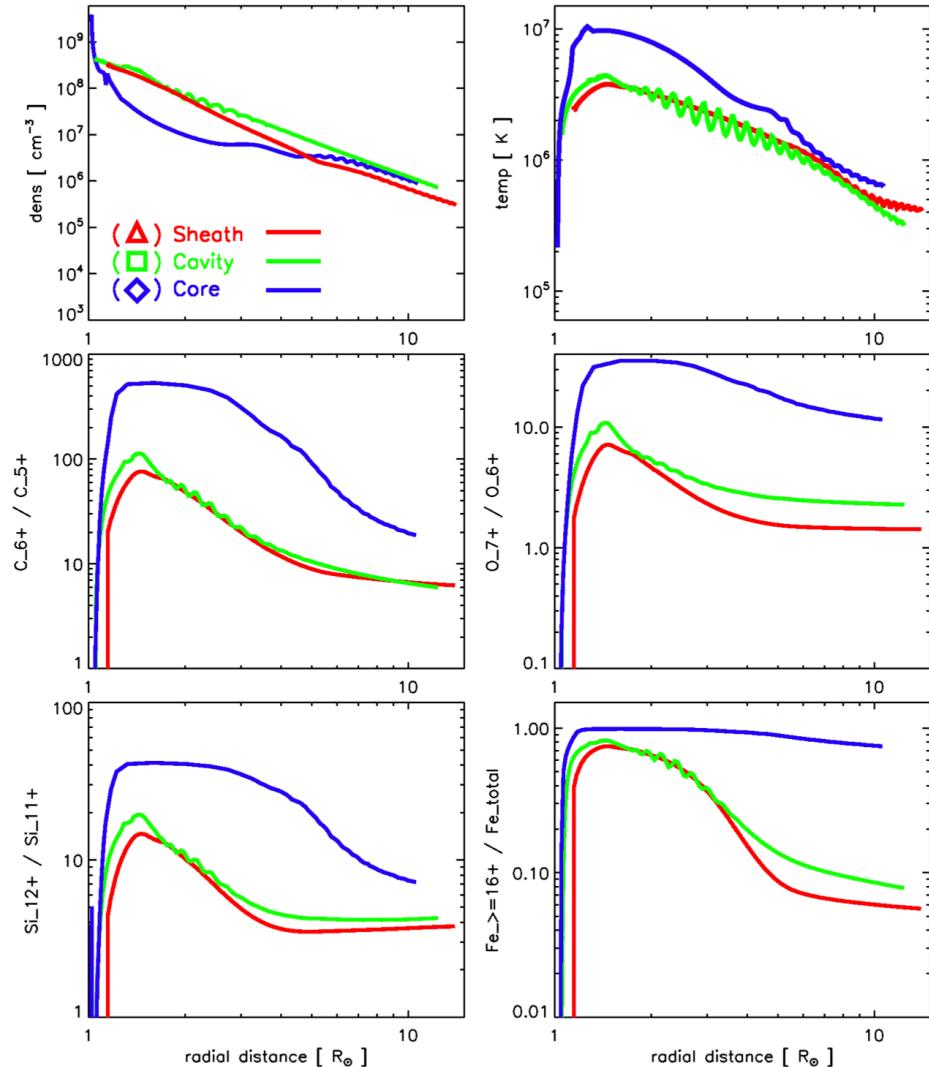
(b) ARC7 / breakout



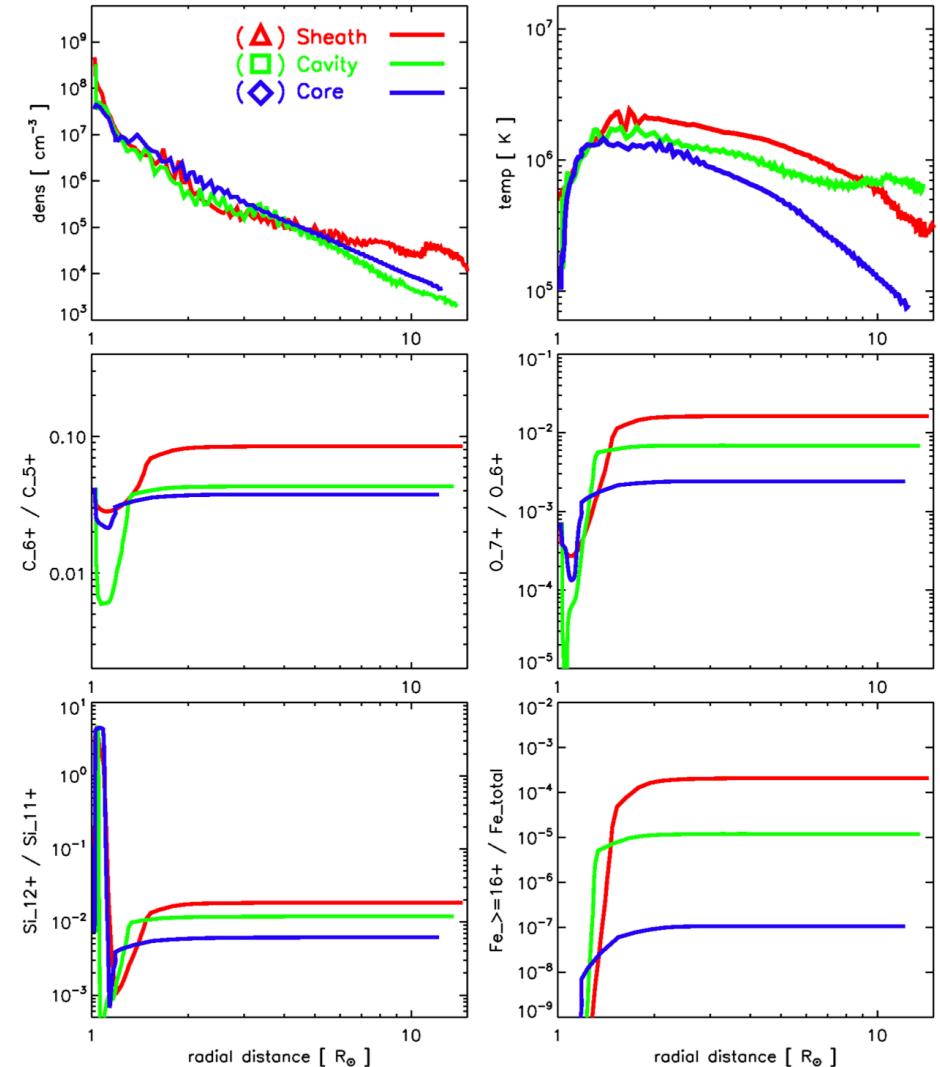
Lynch et al. (2011)

Flux-Cancellation
Breakout

(a) MAS / flux-cancellation



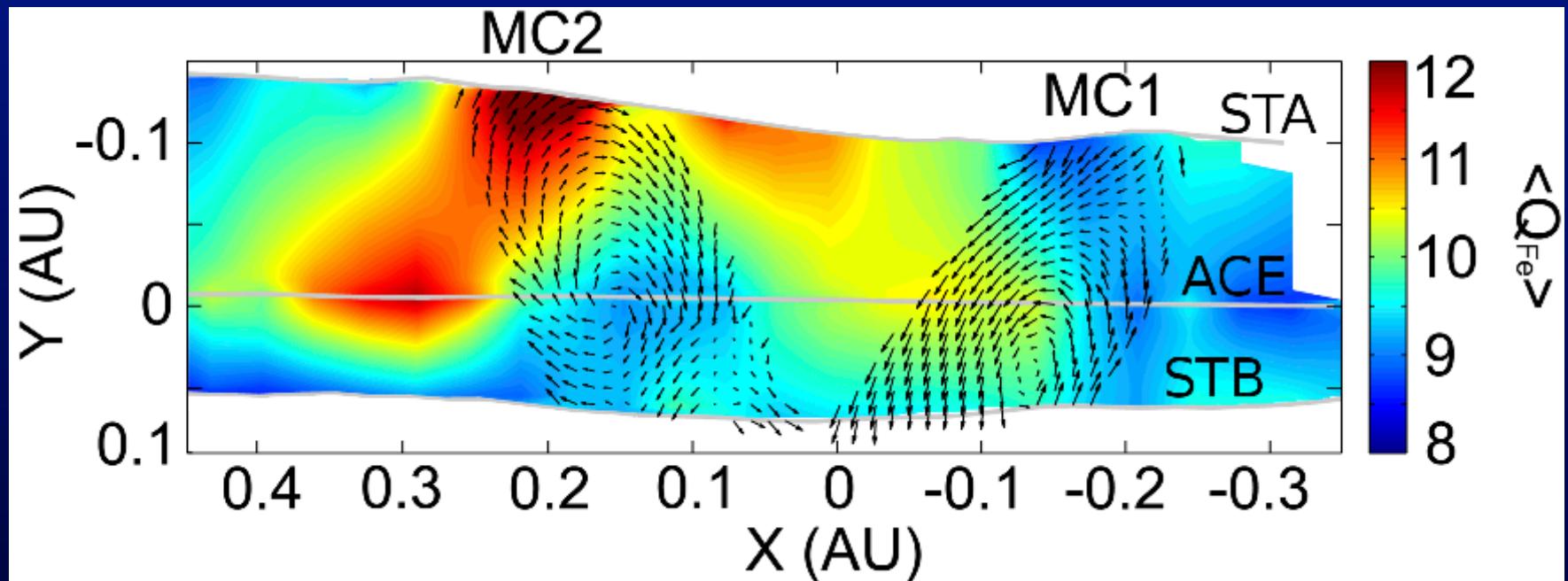
(b) ARC7 / breakout



Lynch et al. (2011)

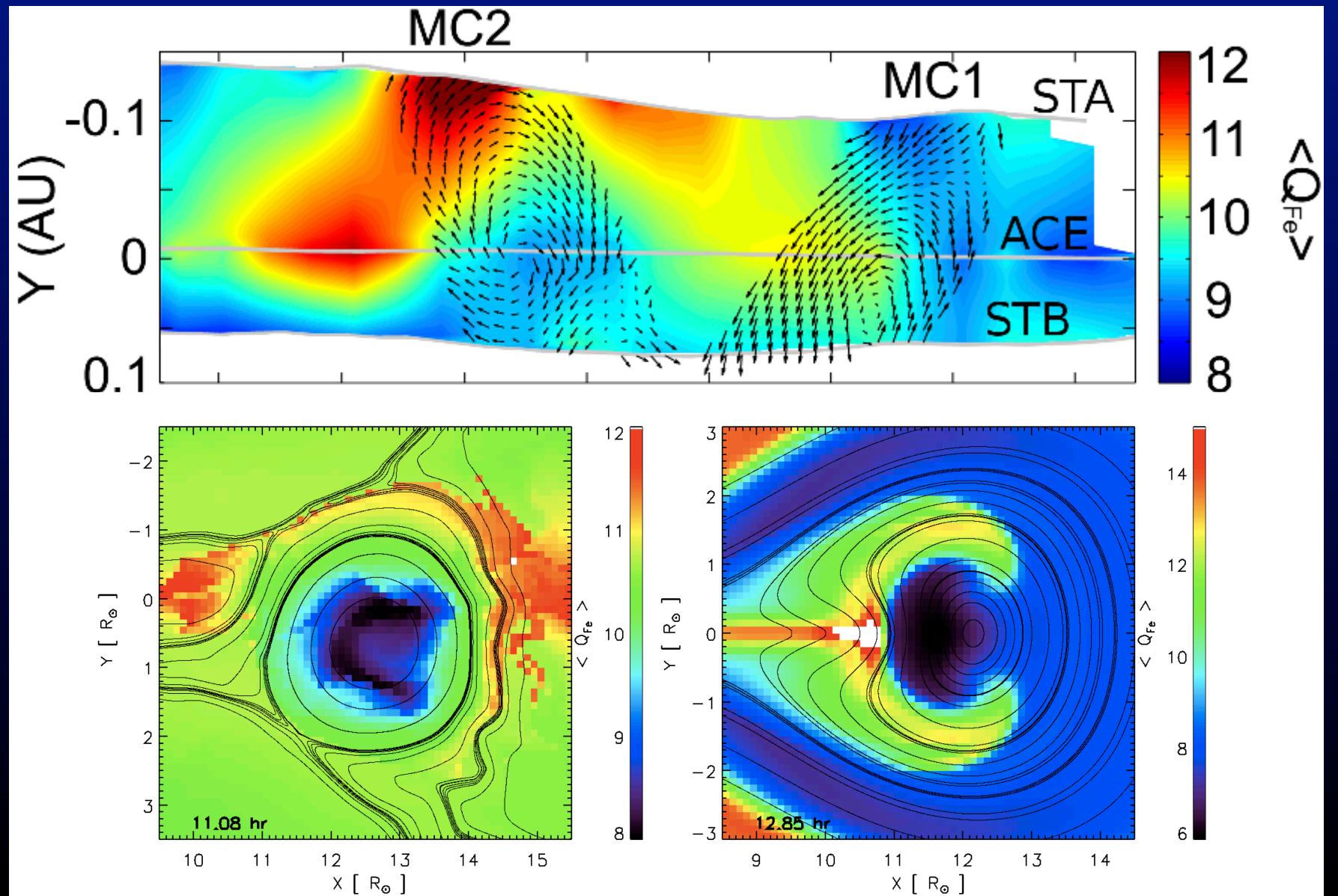
Reinard et al. (2012) Spatial Map of Average Iron Charge State $\langle Q_{Fe} \rangle$

Ionic charge states freeze-in early in the eruption → probe of coronal density, temperature, and eruption properties. Now we can view plasma history of CME FR/sheath/surroundings.

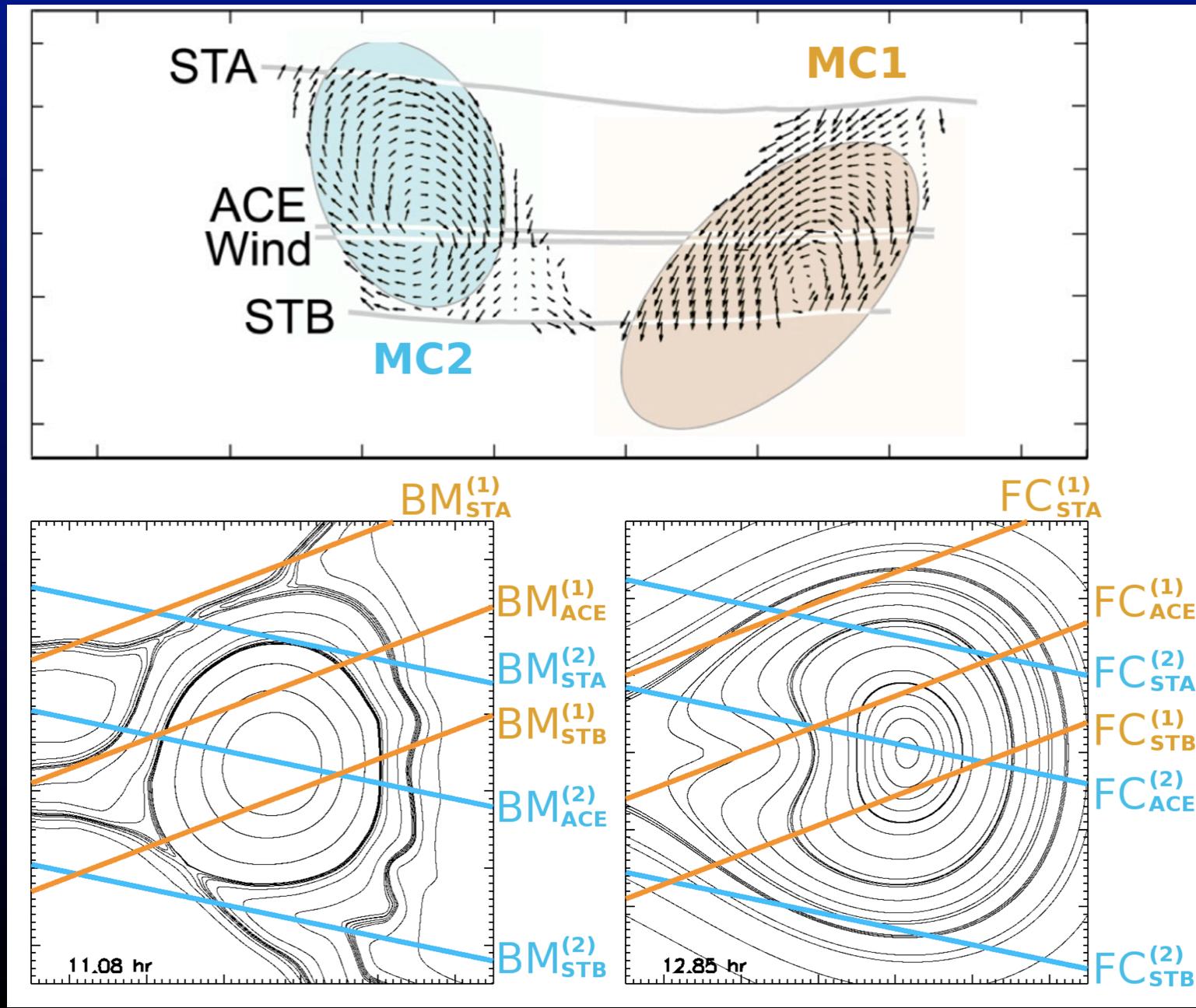


Reinard et al. (2012) Spatial Map of Average Iron Charge State $\langle Q_{Fe} \rangle$

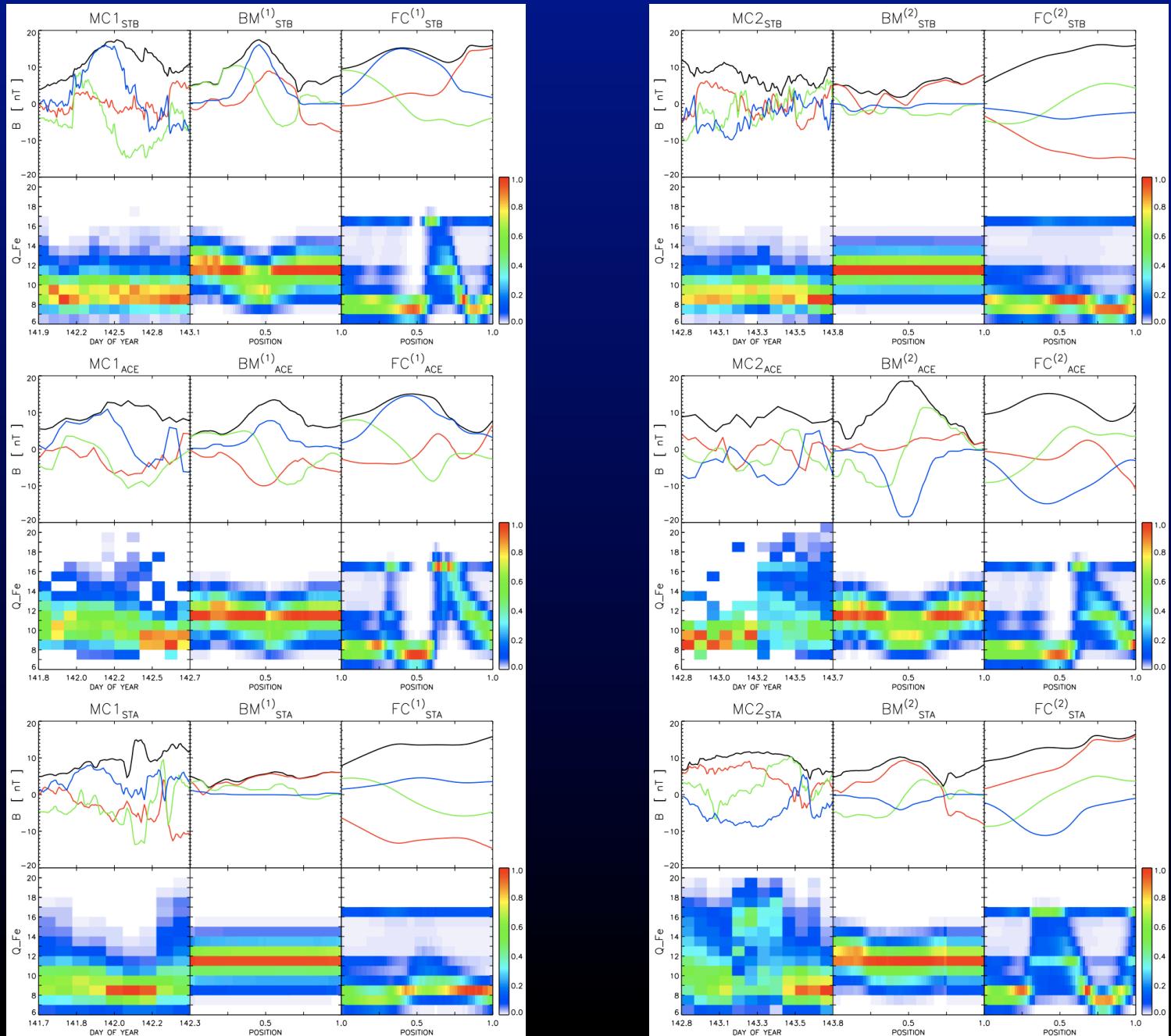
Compare with recent Lynch et al. (2011, ApJ, 740, 112) MHD simulations deriving charge states from MHD simulations of CME initiation (Breakout Model, Flux Cancellation Model).



Comparisons of Full Iron Charge State Distribution Q_{Fe} : Synthetic Spacecraft Trajectories

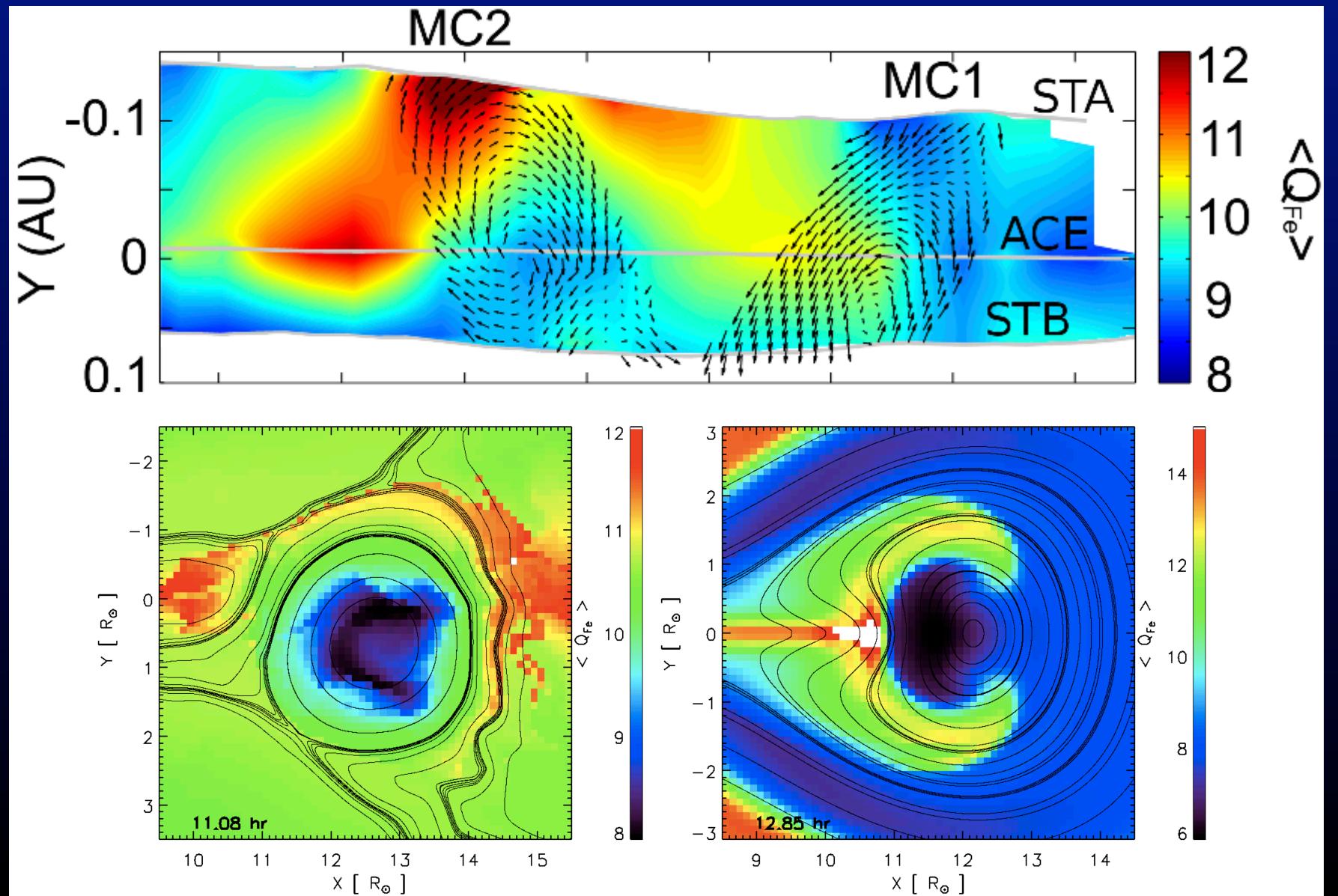


Comparisons of Full Iron Charge State Distribution Q_{Fe} : Observations & Simulation Results



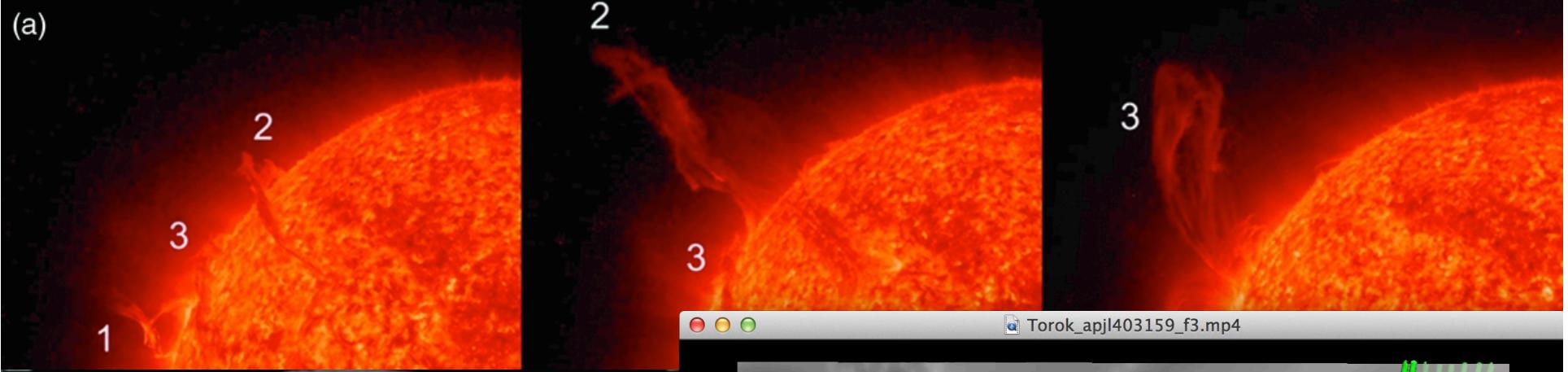
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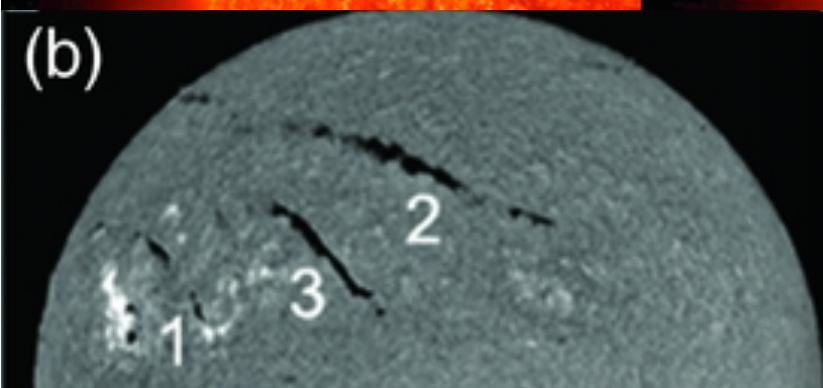


2010 August 1 Consecutive Eruptions – (#1) 02:56UT, (#2) 09:16, (#3) 22:06 (Török et al., 2011)

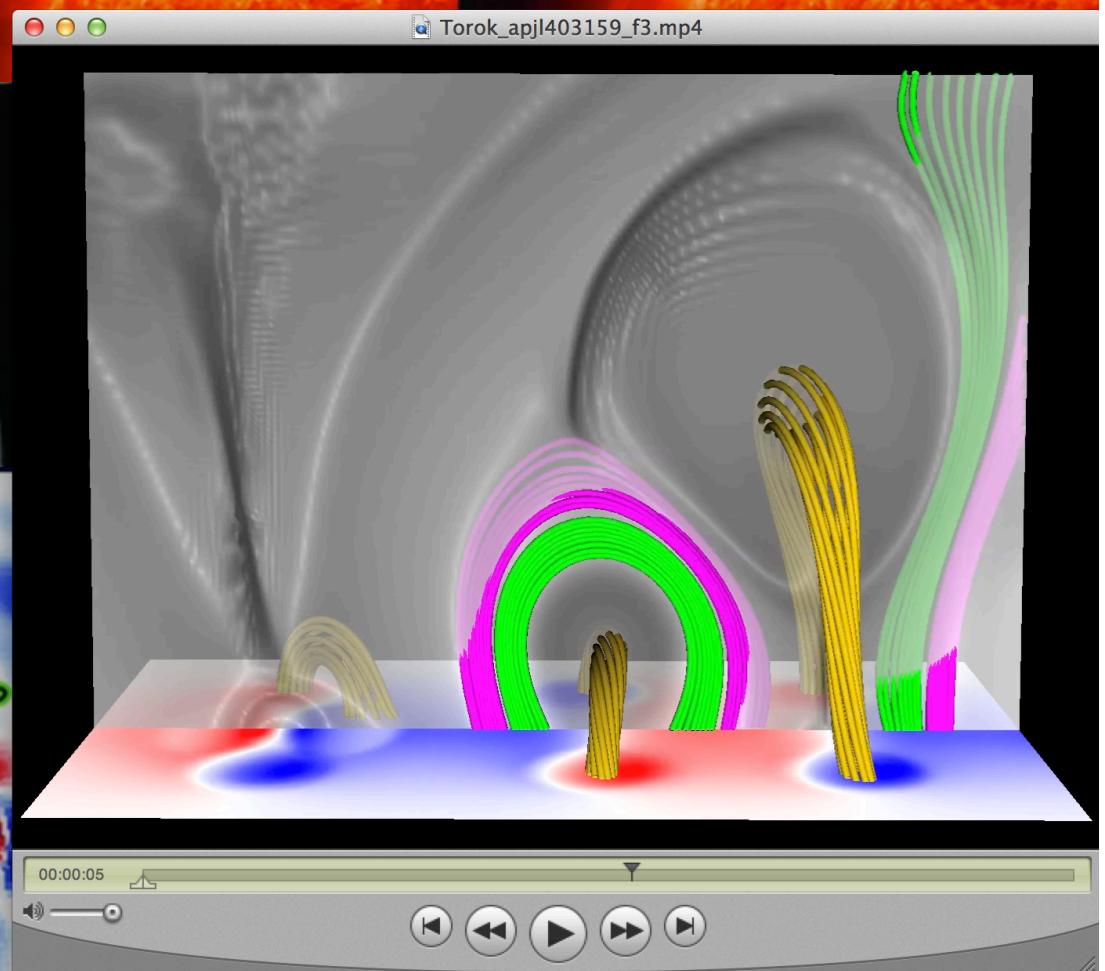
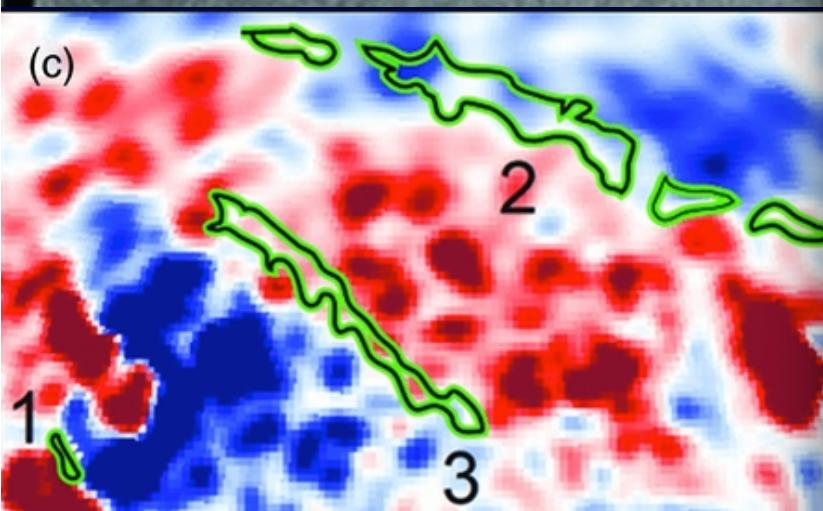
(a)



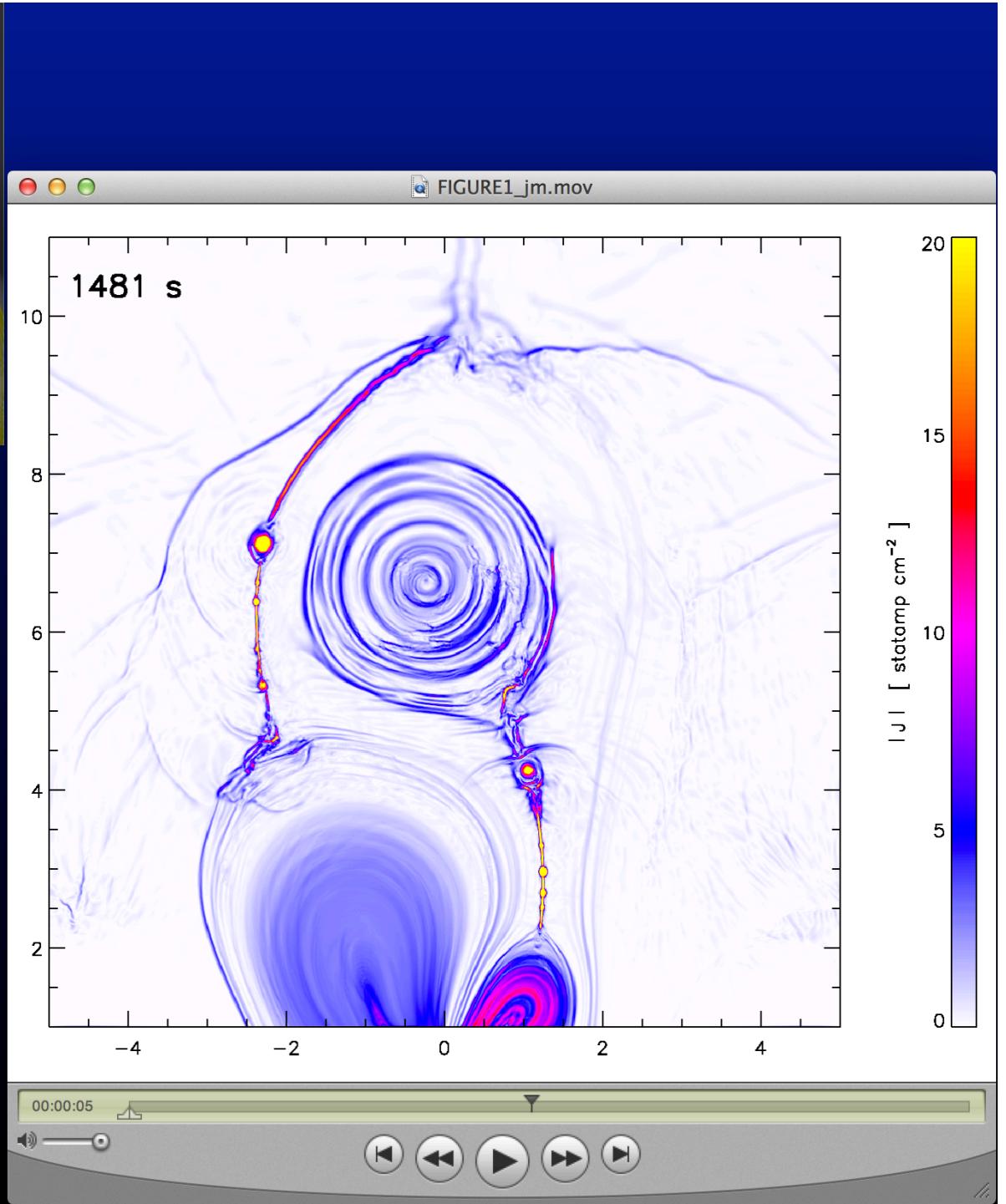
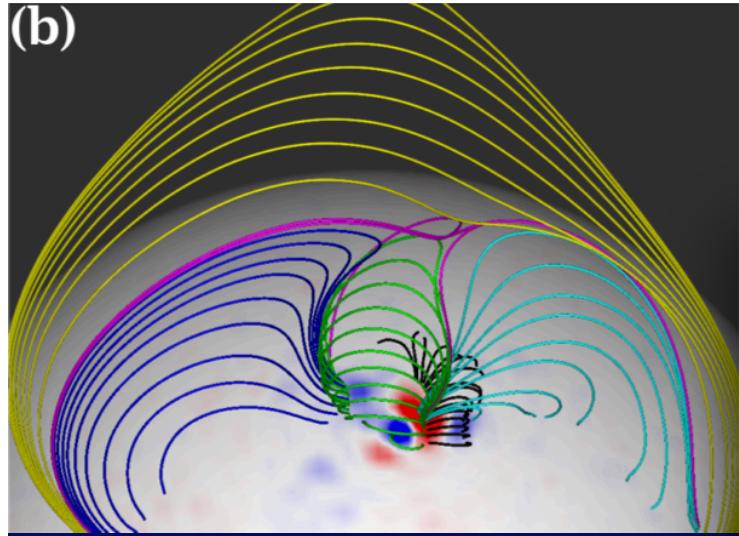
(b)



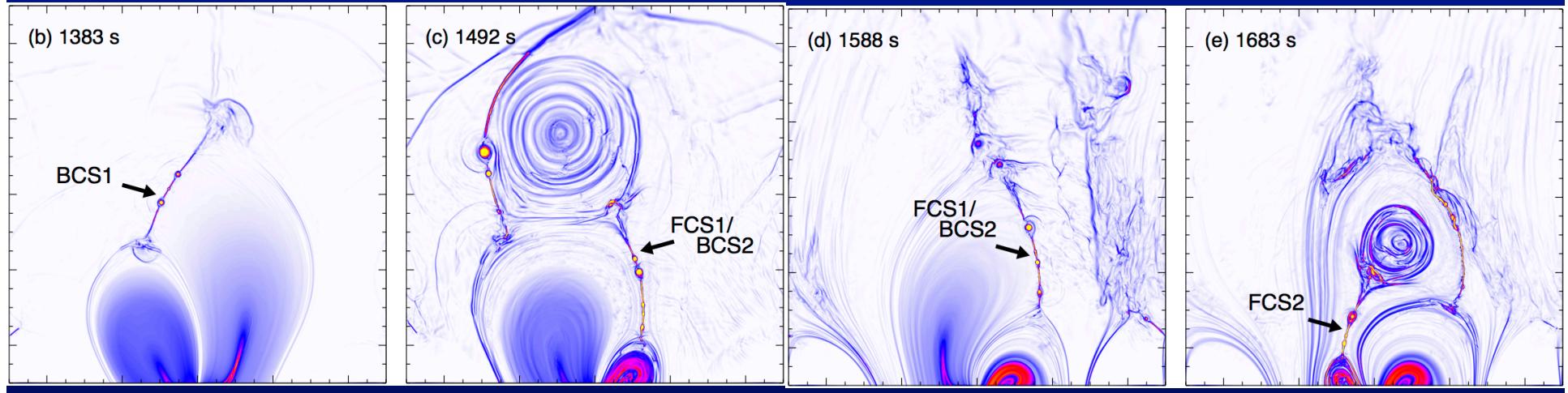
(c)



(b)



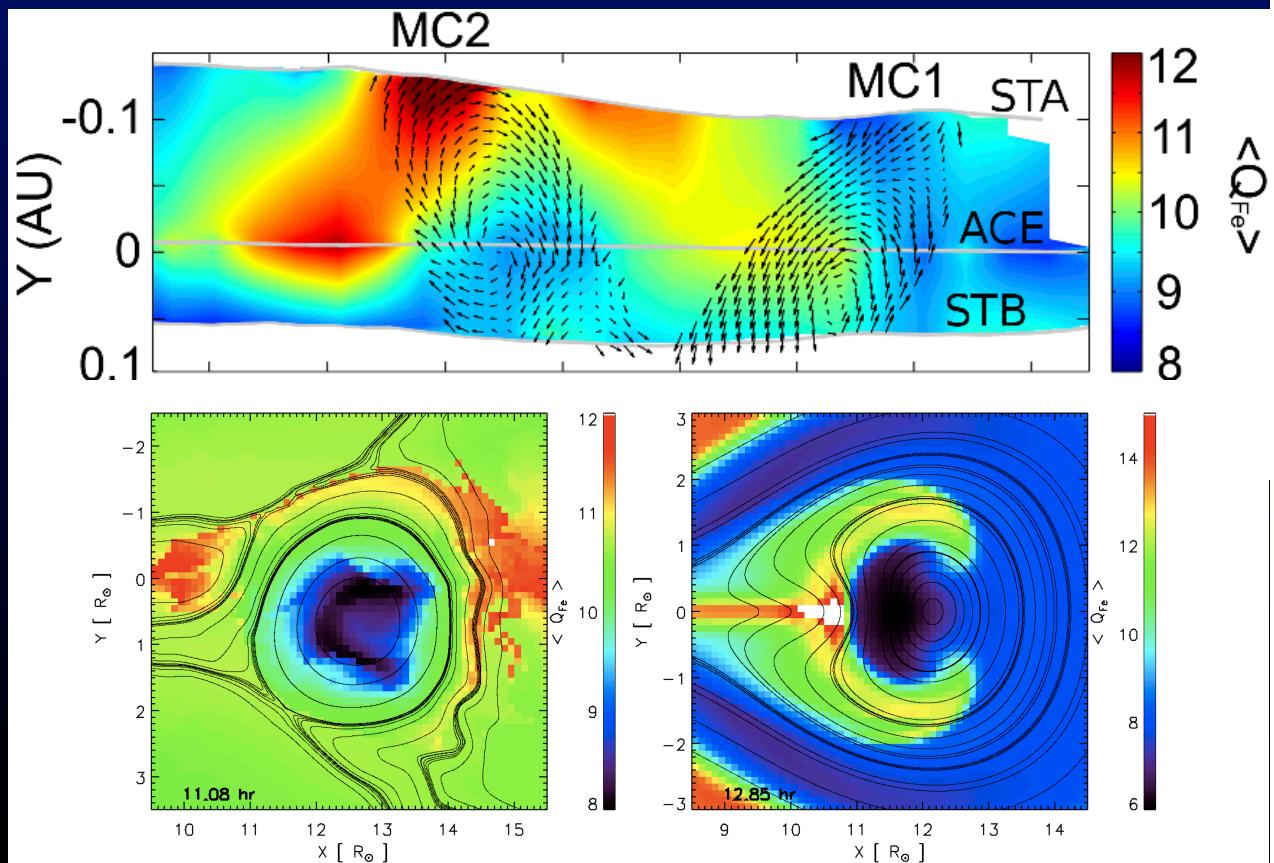
Interpreting $\langle Q_{Fe} \rangle$ Map & Simulation Results: The “Story” of the 19–20 May 2007 Eruptions



Source region observations show adjacent flux systems erupt consecutively.

Need to explain:

- Minor $\langle Q_{Fe} \rangle$ enhancements in MC1, dual-peak hot iron dist. in interior of MC2
- Enhancements trailing BOTH FRs
- The “connection” of enhancements between MC1, MC2



CONCLUSIONS:

1. Multispacecraft spatial mapping/interpolation technique is a valuable new tool for visualization and interpretation of ICME and heliospheric structure
 - Easy to compare to global MHD simulation results, e.g. ENLIL/SWMF/etc
2. Aspects of 21–23 May 2007 ICME charge state signatures similar to those derived from BOTH magnetic breakout AND flux cancellation simulations
 - Reasonable agreement on flare-produced hot iron (16+) in FR interior – dual peaked Q_{Fe} distribution
 - Reasonable agreement on mildly-enhancements around the exterior of the ICME FR
3. Able to interpret seemingly complex events w/ use of “simple” models
4. Lots of future work! Parameter studies, constrain MHD modeling –
 - background solar wind, coronal heating
 - energy release and partition in eruptive flares
 - contribution to + distribution within CME ejecta of flare-heated plasma